THE APPLICABILITY OF WEBER'S LAW TO SMELL.

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CONTENTS.

INTRODUCTION.

So long ago as 1834, in a paper entitled "De Tactu," Ernst Heinrich Weber first stated the law which bears his name, the first law of psychophysics. Working by the method afterwards called by Fechner "the method of just noticeable differences," he had discovered the law in its application to pressure and strain.[1] Before 1860 it had been proved to hold also for noise and brightness. Since the establishment of the first psychological laboratory, which occurred in the academic year 1878-9, and, oddly enough, but a few months after Weber's death, the validity of the law for the four sensation qualities mentioned has been over and over again confirmed.

Before 1860 Volkmann, Renz, and Wolf, by the method of minimal changes, had proved its applicability to noise. Bourger, Fechner, and

[1] Wundt: *Physiologische Psychologie*, 4th ed., I, p. 381.

Volkmann, by their "shadow-experiments," and Masson with his rotating disks, had shown its validity for brightness. Fechner had also established Weber's conclusions in regard to strain by the method of right and wrong cases. In the last twenty years, Tischer, Merkel, and Starke, by the method of minimal changes; Merkel and Angell by the method of mean gradations; and Lorenz, Merkel, and Kämpfe, by the method of right and wrong cases, have confirmed for noise-intensities the results of Volkmann; Helmholtz, Aubert, and Kräpelin have established for brightness the results of Masson; and Merkel, using the method of minimal changes, has also proved the conclusions of Weber and Fechner in regard to strain. In the last six or seven years, the experiments of Merkel by the method of average error have proved the extension of the law to those strain-sensations in terms of which we measure distance by the eye, and the experiments of Schumann by the same method give some indication of its extension to strain-sensations involved in our estimate of intervals between one-half second and three seconds.

In case of the sensation-modalities for which the law has not been proved, and in the case of tone, there are great difficulties in graduating the intensity of the stimulus. Articular sensations, indeed, are not themselves graduated intensively. In the case of tone, the difficulty is mechanical,—that of graduating minutely the objective intensity of simple periodic vibrations. In the case of the two temperature qualities, which are peculiar in depending on different intensities of a stimulus from a physical point of view the same in kind, and in passiug into each other through a conscious indifference-point, the extreme adaptability of the so far unknown and inaccessible peripheral organ makes the intensity of the physiological stimulus begin to fall towards the indifference-point upon the application of any new physical stimulus, and thus prevents the physical stimulus from being a measure of the physiological. The sensation, moreover, varies in intensity with the extent of surface stimulated and with the weight of the stimulating body.

The qualities of taste and smell form manifolds of indefinitely related terms, which must be investigated separately. In the case of taste, the list is at least closed. The intensity of the taste sensation, however, is a function (1) of the degree of saturation of the solution tasted; (2) of the magnitude of the area excited; and (3) of the movement, diffusion, and pressure of the substance tasted within the buccal cavity. No very satisfactory way of keeping all but one of these factors constant, while that one is varied, has as yet been found, though the investigations of Camerer, who worked by the method of right and wrong cases, make the law of Weber appear to apply to salt and bitter.

As for the applicability of Weber's law to smell, the object of this paper is to offer a mass of experimental difference-determinations, with a statement of the "checks" or controls to which they must be subjected. This enumeration of possible

errors involves a discussion of the essentials of a satisfactory olfactometric method, and a detailed description of the method and apparatus actually employed. The literature of difference-determinations in smell amounts practically to pages 180-181 and pages 188-194 in *Die Physiologie des Geruchs* of Dr. H. Zwaardemaker, now professor of physiology in the University of Utrecht. The work was translated into German from Dr. Zwaardemaker's manuscript by Dr. A. Junker von Langegg, and was published in Leipzig in 1895. The experiments to be described are in the main a realization of suggestions of Dr. Zwaardemaker's, of which some are contained in his book, and some few were made in personal letters. The olfactometric method used was, of course, his. This method was first applied in 1888, and is now familiar in most psychological laboratories. To quote from *Science*, XV, 44: "Dr. Zwaardemaker of Utrecht has constructed an instrument which he calls an olfactometer. It consists simply of a glass tube, one end of which curves upward to be inserted into the nostril. A shorter movable cylinder made of the odoriferous substance fits over the straight end of this glass tube. In inhaling, no odor is perceived so long as the outer does not project beyond the inner tube. The farther we push forward the outer cylinder, the larger will be the scented surface presented to the inrushing column of air, and the stronger will be the odor perceived."

We are indebted to Dr. Zwaardemaker for the words "olfactometry" and "olfactometer" (replacing the older "osmometer"), "odorimetry" and "odorimeter." Olfactometry is that branch of psychophysics which is concerned with the measurement of the keenness of smell.[1] The distinction between the keenness and the delicacy of smell must be kept in mind. On the delicacy of smell depends the discrimination of olfactory qualities. On its keenness depend the bare sensing of odors and the discrimination of them as more or less intense.[2] Odorimetry is a "side-issue" of olfactometry. It is concerned not with the sense-organ, but with the measurement of the intensity of smell-stimuli considered as objectively as possible.[3] For the unit of keenness of smell, Zwaardemaker uses the word "olfactus," and for the normal stimulus-limen for each odorous substance he employs the companion word "olfacty."[4] If, for example, a subject's stimulus-limen on the olfactometer is 10 mm. when the normal stimulus-limen used is

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[1] *Die Physiologie des Geruchs*, p. 78.

[2] P. 11. *Cf.* also Vintschgau, *Die Physiologie des Geruchsinnes und des Geschmacksinnes*, in Hermann's *Handbuch der Physiologie*, III, 2, p. 270.

[3] Zwaardemaker: *op. cit.*, p. 174.

[4] Pp. 92, 134-135.

5 mm., then his stimulus-limen is two olfacties, and his olfactus ½. The olfacty used by olfactometry becomes for each substance the unit of odorimetry. Odorimetry is correlated with photometry and phonometry. Both olfactometry and odorimetry are branches of "olfactology" (to anglicise another word used by Dr. Zwaardemaker). This again is correlated with optics, acoustics and haptics.

The interdependence of olfactometry and odorimetry is not unique. The unit of photometry, *i. e.*, the unit for the measurement of light in the physical sense, is the illuminating power for sensation of the light of some standard candle. "We have no adequate objective method," writes Prof. Külpe, "of ascertaining the intensity of the non-periodic and aperiodic concussions which form the substrate of simple or complex noises, independently of the statement of the observer whose sensitivity we are testing. The phonometric determination of sound intensities in psychophysical experiments is usually carried out upon a principle similar to that employed in photometry. As the objective stimulus-values in the apparatus employed,—say, elastic balls falling from a measurable height on a resisting plate,—are determined by way of a subjective comparison, the results are purely empirical, valid only for the material used, the special circumstances of the observation, etc."[1]

The peculiarly unsatisfactory character of the determinations of olfactometry and odorimetry is due chiefly to the fact that olfactory qualities, unlike visual and auditory, are not demarcated. It is true that it is more difficult to keep uniform the duration and extension of smell-stimuli than it is to regulate these attributes for other stimuli, with the possible exceptions of temperature and taste. It is also true that the great gulf of psychophysics, our ignorance of the physiological processes which everywhere link the strictly physical to the psychological, is wider in the cases of temperature, taste and smell, than in the cases of vision, audition, pressure and strain. Yet, at best, the measurements of physics must always be in terms of sensation, and the measurement of sensation must always be in terms of physics.

It seems wise to emphasize at the outset the initial difficulty which makes all quantitative work in smell more or less unsystematic, viz., the indeterminateness of olfactory qualities. It is at present necessary to regard as a simple and separate quality the odor of every substance which from a physical point of view is unmixed; yet, for several reasons, it is un-

[1] *Outlines of Psychology*, tr., p. 156.

likely that there are as many elementary odors as there are simple substances.[1]

One reason is, that it is extremely improbable that either the structure of the fibres or endings, or the substance of the olfactory nerve, is differentiated to correspond to the innumerable odorous substances which we encounter; and, on the other hand, it is probable by analogy with other sense-organs, that there are "specific energies" of smell which are limited in number and capable of combination.[2]

A second reason is that we have experimental evidence that the action of the sense organ is differentiated into more and less separable processes. We have sure evidence in the results of exhaustion-experiments, which were first instituted by Frölich and Aronsohn.[3] For example, a subject whose organ is fatigued by the continuous smelling of tincture of iodine can sense ethereal oils and ethers almost or quite as well as ever, oils of lemon, turpentine and cloves but faintly, and common alcohol not at all. We have also evidence of some slight value in the recorded traces of partial anosmia.[4] Unfortunately, very few such cases have been described by persons who took experimental precautions, and such cases as are noted in medical literature fail to show typical anomalies comparable to the uniform phenomena of color-blindness or "tone-islands," which have played such an important part in the formation of theories of vision and audition.[5]

A third reason is that there are countless instances of smell-fusions in which the components cannot be detected. Nagel intimates that there is no proof of the existence of smell-fusions in which different components can be sensed as different at the same instant, and points out that, in this respect, smell-mixtures resemble color-mixtures rather than clangs.[6]

Zwaardemaker, following Aronsohn and bearing in mind the usages of the perfume trade, holds that only similar odors will

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[1] It should be noted that the words "simple" and "mixed" or "compound" are used here in the sense of physics proper, and not in the sense of chemistry. Smell, in the physical sense, is undoubtedly a property of the molecule, not of the atom. Indeed, most of the elements are odorless. Sulphur and hydrogen, themselves odorless, form sulphuretted hydrogen, one of the most offensive smelling gases known.

[2] Nagel: *Über Mischgerüche und die Komponentgliederung des Geruchsinnes. Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, XV, pp. 82-83.

[3] Zwaardemaker: *op. cit.*, pp. 203, 204, 256-257. Aronsohn: *Untersuchungen zur Physiologi des Geruchs. Archiv für Physiologie*, 1886, pp. 342-346.

[4] Zwaardemaker: *op. cit.*, p. 259 sq.

[5] Nagel: *op. cit.*, p. 87.

[6] Pp. 90-91.

mix.[1] He believes, on the basis of his own experiments, that if dissimilar odors of different intensities are mixed, the weaker odor will cancel part of the odor of the stronger, and will itself be lost, and that if dissimilar odors of the same intensity are mixed, both will disappear or will give but a feeble indeterminate fusion.[2] Zwaardemaker does not, as alleged by Nagel, adduce his conclusions in regard to mixture as a buttress to his localization and irradiation theory, though he does seek to explain the facts of mixture and compensation, as he understands them, in harmony with this theory.[3] Nagel, as opposed to Zwaardemaker, believes, on the basis of his own experiments, that any two smells will unite in a mixture which for an instant, at least, will make a simple impression of new quality.[4] He has never found an instance of complete "compensation," but he agrees with Zwaardemaker that a mixture of several smells is in general weaker than its individual components, and that some combinations of strongly odorous substances are almost odorless.[5] Nagel offers no explanation of the phenomenon of compensation, nor does Zwaardemaker explain it satisfactorily even on the basis of his irradiation-theory. Perhaps it is safe to conclude that most smells will mix. As Nagel suggests, there is no occasion in the perfume trade to mix nauseating or hircine smells with the odors of flowers, spices and resins.

A fourth and final reason for believing that there are not as many simple odors as there are unmixed substances, is that many simple substances have been found by experiment to have composite odors. Chlorphenol and nitrobenzol are good examples of such substances.[6]

Now, if there are a limited number of specific energies of smell, and if most smells are mixed, our ignorance of the elementary smells, and our consequent inability to isolate them, have serious consequences for the value of olfactometric work. This will be clearer if we consider the two methods which are used to discover whether a smell is simple or composite. The method of Passy consists in gradually increasing the dilution of odorous substances, and depends upon the principle that since the stimulus-limina of different odors are different, they must disappear successively as the intensities of the different stimuli are diminished equally.[7] However, it is at least possible that

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1 *Op. cit.*, p. 280.
2 Pp. 167 and 284.
3 P. 279.
4 *Op. cit.*, 95.
5 P. 101.
6 Pp. 96-97.
7 P. 96.

odors which have very different stimulus-limina should have the same difference-limina. The other method is that of exhaustion, and depends on the fact that different odors exhaust the organ with different degrees of rapidity, so that a compound odor, continuously smelled, will alter in quality as first one and then another of its constituents disappears. One may smell continuously the substance to be tested, or may smell it before and after smelling repeatedly an odor very similar in quality. The principle of the method is the same in both cases. The permanency of the mixed odor depends primarily on the equality of rate at which its different constituents fatigue the organ. The more numerous the constituents, the more permanent the quality of the mixture. This fact is well recognized in the perfume industry. Fortunately for the trade, the odor of almost every flower (Sawer mentions jasmine as a unique exception)[1] may be simulated by compounding the odors of other flowers. The odor of violet, for example, is given by a blend of the odors of acacia, rose, Florentine iris, tuberose and almond. The odors of most flowers, again, are possessed by certain chemicals. To the mixture is usually added some substance, such as styrax, amber, or vanilla, which evaporates slowly, and smells strongly enough to compensate parts of the other odors. This is done that quantities of the other odorous substances large enough to allow for evaporation may be put into the solution without raising the intensity of the smell to the neighborhood of the terminal stimulus-intensity.[2] If, now, most smells are mixed, and if mixed smells alter in quality as the organ becomes fatigued, and if different olfactory qualities have not the same limina, then in quantitative work in smell, we are seeking to determine values which are continually changing according to laws which we do not know.

There is no classification of olfactory qualities, which is even provisionally satisfactory from any point of view but a perfumer's. We give to odors the names of the objects which most commonly give rise to them, or to something similar to them. We speak of a "fishy smell" as loosely as Homer, in the days when the terminology of color was in its infancy, spoke of "the wine-hued sea." Yet the name of an odor is clearly and indisputably applicable only to the smell of that object from which the name is taken.[3]

Giessler's classification of odors may be of value to psychology proper, but is of no value whatever to psychophysics.

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[1] Sawer: *Odorographia*, First Series, p. 94.
[2] Zwaardemaker: *op. cit.*, p. 285.
[3] P. 208.

The most satisfactory method of arriving at a classification of smells seems to be the method of exhaustion; but the results so far obtained do not furnish any basis for such a system. Nagel points out as the greatest difficulty in the way that when the organ is fatigued by one smell, its sensitivity does not remain quite unimpaired for one large group of odors, and utterly fail for another group; but on the contrary, is usually more or less impaired for all odors.[1] Analysis by exhaustion is complicated experimentally by the fact that smells do not fall away steadily, but oscillate at the stimulus-limen, as do minimal sensations in other departments. In the case of smell this oscillation depends on slight variations in the rate and manner of breathing, as well as on the ordinary ebb and flow of the attention. The apparent "rivalry" of odors is due to this fluctuation at the limen.[2] Moreover, it is only the last component of the mixture to disappear, which is ever really isolated by the exhaustion-process.

Zwaardemaker adopts, with some modification, the old classification of Linnæus, which really has only a subjective basis, though Zwaardemaker attempts, without signal success, to give it a chemical one. On the principle that even a most unsatisfactory system is better than none, some pains have been taken in the experiments to be described to procure smells from as many of Zwaardemaker's classes as possible, and to compare results for representatives of the same class and of different classes. Zwaardemaker's classes of pure olfactory qualities are as follows:[3]

I. Ethereal smells—including all the fruit odors (a class taken from Lorry).

II. Aromatic smells—including all such odors as that of camphor, spicy smells, and the odors of anise and lavender, lemon and rose, and almond.

III. Fragrant smells—including the odors of most flowers, of vanilla, and of such gums as tolu and benzoin.

IV. Ambrosiac smells—including the odor of amber, and all the musk odors.

V. Alliaceous smells—including the odors of garlic, asafœtida, gum ammoniac, vulcanized India rubber, fish, bromine, chlorine and iodine, etc.

VI. Empyreumatic smells—including the odors of toast, tobacco smoke, pyridin, naphtha, etc., (a class taken from von Haller).

VII. Hircine smells—including the odors of cheese, sweat, rancid fat, etc., etc.

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[1] *Op. cit.*, p. 86.
[2] P. 98.
[3] *Op. cit.*, pp. 233-235.

VIII. Virulent smells—including such odors as that of opium, "Odor cimicis," etc.

IX. Nauseating smells—including the odors of decaying animal matter, of fæces and the like.

The pungency of smells is not an olfactory quality, but is due to the excitation of filaments of the trigeminus, which are freely distributed in the Schneiderian membrane. The sensation is more like pressure than smell. When very strong it becomes a tickling, and sneezing ensues. Persons who have congenital or pathological defects of smell are said to have cultivated these sensations by attention to such an extent that they do duty for smells proper.[1] Some smells which are not the flavors of food sensed in expiration, seem to be tastes, as well as smells. For example, we think of the odor of boiling syrup as sweet, and say that curdled milk "smells" sour. This is probably due to early association, which has indissolubly fused certain taste-memories with certain smell-sensations of peripheral origin.[2] It may, however, be due to the entrance of sapid particles through the nose into the pharynx.[3] Smells are often blended with pressure sensations other than pungency and with temperature sensations.[4] It is probable that there is an element of pain in an impression of pungency, while smells often give a "feeling of weight," pure and simple. Whenever the subjects in these experiments spoke of the heat, taste, pressure, pain, or pungency of an odor, their remarks were carefully noted, on the supposition that such factors in the total impression were disturbing in a quantitative investigation of olfactory qualities proper.

Zwaardemaker's differentiation of the specific energies of smell and localization of their actions on the olfactory mucous membrane is not to our present purpose. We may simply note in passing that he arranges the zones of their operation in horizontal order, since the height to which the air current is carried in the nose makes no difference in the quality of an odor; and that he rather ingeniously places the nauseating and virulent smells farthest back and closest to the pharynx, in a region where they may excite the reflexes of vomiting and coughing by mere irradiation of nervous excitation without the connecting link of central processes; puts the hircine and ambrosiac odors in the middle, on account of the connection of hyperaemia of the "corpora cavernosa nasalia" with the blood supply of the generative organs; and locates the fragrant, aromatic and ethereal smells farthest to the front, since the

[1] Pp. 236-237.
[2] P. 211.
[3] Pp. 211-212.
[4] P. 212.

sneezing-reflex is most easily excited in the anterior portion of the nasal cavities.[1] Nagel's remark that Zwaardemaker's localization-theory leads to "irresolvable contradiction" is not quite clear, but he is certainly right in saying that the theory has no adequate basis. Aside from the lack of experimental evidence, the arrangement of the several zones is too fancifully neat to carry conviction with it; but Zwaardemaker himself emphasizes the fact that the essential part of his theory is simply the arrangement of the operations of specific energies of smell corresponding more or less exactly to the classification of Linnæus on the olfactory mucous membrane in the order of these classes.[2]

Before bringing these introductory remarks to a close, it may be noted that, aside from any experimental evidence which may be offered, it is probable that Weber's law does apply to such smells, mixed and unmixed, as we daily encounter. In the first place we have the analogy of several other modalities of sensation for believing that the law applies to simple olfactory qualities. In the second place it has never been proved that Weber's law applies merely to unmixed sensations. It has been neither proved nor disproved for clangs, but many experiences of ordinary life would lead us to believe that it does apply to musical chords as wholes. Thus it may apply to smell-fusions as wholes, and approximately correct difference-determinations may be obtained for these wholes even while their character is gradually altering. Since, in the present state of our knowledge, no one can even pretend to be working with simple olfactory qualities, all difference-determinations in smell must proceed upon the assumption of this possibility. Experimental results must be the only decisive evidence for or against the theory, so that it is needless to discuss it farther in this place.

In the third place the distinction drawn by Passy between "insistent" and "intensive" smells, which is based upon a classification of smells in the popular mind and confirmed by other scientific men, is explained by the supposition that Weber's law applies to smell with different values of $\frac{\Delta r}{r}$ for different qualities. In Zwaardemaker's language, and in the ordinary language of this paper, the smaller the "minimum perceptible" of a substance, the more intense its odor. Passy uses a term, "pouvoir odorant,"—which we may translate "insistency,"—for "intensity" in our sense. He says: "Tout le monde sent que le camphre, le citron, le benzine sont des odeurs for-

[1] Pp. 262-265.
[2] P. 265.

tes, la vanille, l'iris des odeurs faibles,'' though vanilla has an insistency one thousand times greater than that of comphor. Besides this subjective basis of distinction between weak odors, however insistent, and strong or intensive odors, he has five objective differentiæ. (1) Weak smells have vague differences of intensity. For example, vanilla and coumarine soon reach a maximum of intensity which cannot be increased. Greater concentrations simply become unpleasant. (2) Individual differences are more evident for weak smells. (3) The daily variations of sensitivity are more evident for weak smells. (4) Exhaustion has more effect on weak smells. (5) Strong smells hide the weak.[1] In view of the first objective difference, Zwaardemaker explains the subjective difference as follows: As the strength of a sensation is estimated by the number of grades of intensity by which it surpasses the liminal sensation, and as the terminal stimulus is by definition that degree of intensity beyond which increase cannot be shown for our human sense organs with our mechanical appliances, it is obvious that odors with large difference-limina must be subjectively weak, and that subjectively weak odors must have large difference-limina. Thus, the very rapid attainment by some smell-stimuli of the terminal intensity would seem to indicate that Weber's law applied to olfactory qualities, and that the difference-limen differed from quality to quality.[2]

Unfortunately our own experimental results are at variance with the second clause of the theory. They make Weber's law appear to apply to smells as we find them, but show no great variation of $\frac{\Delta r}{r}$ from substance to substance. The difference-limina even of camphor and vanilline seem much the same. If our figures are accepted as trustworthy, some other explanation than the simple one of Zwaardemaker must be found for the distinction of Passy. May it not be that, for phylogenetic reasons, "intense" smells have more affective value, more of what Müller calls "Eindringlichkeit,"[3] than have the smells which Passy calls "insistent?" Or may it not be that the smells most useful to human life exhaust the human sense-organ less after many increments than smells less useful do after a few increments, although the increments are relatively equal throughout? The need of some such explanation will be more or less clear as the figures to be offered are more or less convincing.

[1] Pp. 191-192.
[2] Pp. 192-193.
[3] The "Eindringlichkeit" of a sensation depends in part upon its intensity, and in part upon its affective value (G. E. Müller, Zeitschr. f. Psych. und Physiol. der Sinnesorgane, X, pp. 25-27).

CHAPTER I. METHOD.

Section 1. Determination of the intensity of the Smell-Stimulus for the Normal Organ.

If all the nervous elements concerned in smell are in a normal condition, and if "compensation" does not come into play, the intensity of an odor depends on the number of odorous particles in gaseous form which are acting on the olfactory nerve-endings at the time. Perhaps it is safe to say that the intensity is ordinarily a function of the number which are acting on the rod-cells of the olfactory mucous membrane.[1] Whether or not individual rod-cells are subject to cumulative stimulation, we do not know, for we do not know even whether the stimulation is chemical, thermal, or electrical,[2] but we do know that the intensity of the smell seems to depend on the extent of membrane and therefore on the number of rod-cells stimulated,—always supposing that the rod-cells are the olfactory cells proper.

Now the number of odorous particles which act at any given time on the olfactory membrane of the normal nose depends, first, on the quantity of vapor which the fragrant body is throwing off; secondly, on the rate of the diffusion of this vapor; and thirdly, on the manner and rate of breathing. Let us consider these facts separately.

I. *The Quantity of Vapor Thrown off by the Odorous Body.* "Whether" says Zwaardemaker, "odorous particles are set free by evaporation or chemical reaction, the mass of odorous molecules which are given off from a solid body or the surface of a liquid is, *ceteris paribus*, in compound proportion to the time of exposure and extent of surface exposed.[3] Zwaardemaker has invented a "genetic unit" for the measurement of odor in the physical sense. It is the number of seconds of exposure multiplied by the number of square millimeters of surface exposed.[4] It is unnecessary to say that the genetic unit differs from substance to substance. The "other factors" which must remain equal, if the genetic unit of a given substance is to be constant, are the moisture, weight, and temperature of the atmosphere and the amount of ozone present in it.[5]

That heat and dampness affect the intensity of odors is a matter of common observation. Yellow wax smells twice as strong in summer as in winter. Heat promotes evaporation. Dampness also promotes the vaporization of such solids as are

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[1] Zwaardemaker: *op. cit.*, p. 7; Foster: *Text Book of Physiology*, 6th ed., p. 249.

[2] Zwaardemaker: *op. cit.*, pp. 276-277.

[3] P. 39.

[4] P. 26.

[5] P. 28.

soluble in water, but, on the other hand, retards the diffusion of odorous vapors. The temperature of the laboratory in which smell experiments are in progress should be kept as uniform as possible, and thermometer and barometer readings should be taken whenever the stimulus-limen is determined. Uniformity of temperature was not secured in our own experiments.

II. *The Rate of Diffusion of Odorous Vapor.* Cloquet pointed out in 1821 that odors diffuse in the air as one gas diffuses in another,—gradually, and without interruption by reflection or refraction,—so that if the air is at rest, the strength of a smell will be inversely proportional to the distance of its source, though the speed with which different odors travel varies much.[1] Now the air from which we draw our breath is, under ordinary circumstances, almost never free from currents. For phylogenetic reasons, no gas is odorous which is not heavy enough to remain near its source if undisturbed. Yet the wind may carry such gases for miles near the surface of the ground. Nor can we, in view of the dynamic theory of smell, and of Liegois's theory that odorous particles are largely diffused in the form of tiny liquid drops which afterwards vaporize, unhesitatingly apply the laws of diffusion of gases to smells. Zwaardemaker has, however, proved by a series of experiments that the transmission of odorous vapors in tubes takes place at the same rate for different distances from the source, unless these distances are very considerable.[2] From an inhaling-tube, all currents of air, except the suction-current created by the inspiration, are excluded.

III. *The Rate and Manner of Breathing.* Not all the air which passes through the nose comes in contact with the olfactory mucuous membrane. The current of air drawn into the nose from without is divided by the lower turbinal bone into two portions. From the stream which takes the direct path to the choana under this bone and along the floor of the nose, no odorous vapor reaches the olfactory membrane. Each nasal cavity is divided by the middle turbinal bone into two chambers. In the upper chamber, which extends from the pointed roof of the nose to the under edge of the middle turbinal bone, the side wall and the septum are almost parallel, and only about two millimeters apart. The olfactory membrane is spread over the upper surface of these parallel walls, forming the *regio olfactoria* of Todd and Bowman. According to von Brunn only the uppermost part of the upper turbinal bone and the surface of the septum just opposite are covered by the ol-

[1] P. 30.
[2] Pp. 31-34, 39-40.

factory membrane.[1] In ordinary breathing, the highest point in the upper stream is, according to Franke, the under edge of the upper turbinal bone, and according to Paulsen and Zwaardemaker, the under edge of the middle turbinal bone.[2] In the rapid and violent breathing with expanded nostrils which we call "sniffing," the air is carried about 2 mm. higher,[3]—*i. e.*, into the forward and under part of the upper chamber. In either case, odorous particles can reach the olfactory membrane only by diffusion, but more of them will penetrate to it in sniffing than in quiet inspiration. The upper chamber is an annex, not an integral part, of the breathing-passage.

Odorous particles probably do not accumulate in the upper chamber. During inspiration, the air in the passages traversed by the current is thinned, and as soon as inspiration ceases, the air in the upper chamber rushes down to the middle meatus, to be renewed from the pharynx during expiration.[4] If so much odorous matter has been taken in as to saturate the air in the pharynx, we sometimes get a smell in expiration even when we are not eating. Ordinarily, however, the very weak stimulus from the pharynx, coming after the very strong stimulus from without, is not sensed.[5] Fick, indeed, advanced the hypothesis that when odorous particles come in contact with the olfactory membrane, they are at once dissolved in the thin fluid which covers the bottom of the sensitive hairs, and that when so dissolved, they cease to act.[6] These particles may, however, accumulate to some extent on the Schneiderian membrane, especially, if it is in a catarrhal condition. Of course, we get the flavor of food only in expiration. The course of the air in expiration is almost the same as in inspiration, but Bidder is probably right in supposing that a smaller amount passes above the lower turbinal bone.[7]

Under ordinary conditions, the more rapid the breathing, the more intense the smell. Sniffing is to be forbidden in olfactometric work, not merely because it carries the air higher in the nose, than does "regular breathing," but because, both by increasing the suction-force and by widening the entrance, it takes more air and therefore more odorous particles into the nose in a given time. The spaces from which air is drawn through the nose are cones with their points at the nostrils. We may see their size and shape in the clouds of vapor formed

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[1] P. 6.
[2] Pp. 46-57, 67.
[3] P. 202.
[4] P. 60.
[5] P. 62.
[6] P. 60.
[7] P. 42.

by our exhalations in cold weather. The spaces from which odorous particles are drawn are portions of these larger spaces. The breathing-spaces are projections of the whole of the nasal cavities; the "fields of smell" are projections only of those cavities from which odorous particles reach the olfactory membrane. They are separated from each other by about a centimeter. In sniffing, through the expansion of the nostrils, the fields of smell become wider than the ordinary breathing-spaces, but as the inspiration is short and quick, they are not so deep.[1]

If then the strength of a smell-stimulus is to be measured with some degree of accuracy by the genetic unit, the temperature and moisture of the air, the diffusion-rate of the vapor, and the subject's manner and rate of breathing must be kept as uniform as possible.

As for the compensation-error, there is no intrinsic stimulation of the olfactory membrane as there is of the retina and the ear. Owing to exhaustion, the subject cannot smell his own breath in expiration. He can indeed smell it in inspiration if the current is puffed upward to the nostrils. This fact seems to show that, given the same amount of odorous matter in the air current, we get a stronger smell in inspiration than in expiration. On the other hand, the difficulty of securing an absence of smells from external sources for a subject who has at all cultivated his organ by attention, transcends the difficulty of securing such silences and darknesses as are satisfactory for experimental purposes. Of course, no substance which, *as such*, is to be used as a test, should be dissolved in an odorous medium, such as alcohol, ammonia, or ether.

Zwaardemaker classes the methods which have so far been employed to find the stimulus-limina of smells as direct and indirect.[2] By the direct methods the subject seeks to find the stimulus-limen of an olfactory quality in terms of the greatest dilution of an odorous vapor which can give a just noticeable sensation of that quality. By the indirect methods, he seeks to find the stimulus-limen in terms of the smallest quantity of the odorous substance which can be sensed under certain definite and easily procurable conditions. The direct methods aim at absolute results where absolute results are unattainable. "It may be possible," says Zwaardemaker, "to determine the area of an inspiration made in an effort to smell, but the exact ascertainment of the amount of odorous gas which in this inspiration comes in contact with the olfactory cells has so far proved an impossibility."[3] The indirect methods aim at relative results, but their procedure is exact. They furnish a

[1] Pp. 68-77.
[2] Pp. 79-80.
[3] P. 80.

basis for the comparison of individuals with reference to their keenness of smell, and of substances with reference to their value for the sense, and thus may indirectly lead to some knowledge of the greatest degree of dilution in which an odorous substance can be detected.[1]

The method which Valentin invented in 1848 may be called classical, since it is mentioned in most of the standard text books of physiology. It was direct, and consisted in taking a certain volume of odorous gas and mingling it with a hundred volumes of air, taking a certaiu volume of the mixture and mingling this again with a hundred volumes of fresh air, and so on until the last mixture gave a just discernable odor. Valentin varied his procedure by allowing the vaporization of smaller and smaller quantities of a highly concentrated solution of an odorous substance in a definite amount of air, or by mingling smaller and smaller quantities of it with a mass of water of a given volume.[2] It is plain that a certain amount of the odorous substance must adhere to the vessel in which such a mixture is contained, so that the amount of odorous substance taken away from the receptacle for a new admixture will never be so large as the ratio of the gas or liquid removed to the whole volume would indicate, and that this error must increase as the experiment proceeds. As for the use of highly concentrated solutions, it involves two serious disadvantages, the blunting of the sense by exhaustion and the adhesion of odorous particles to objects in the laboratory.[3]

The invention of no other direct olfactrometric method is recorded before that of the method employed by Fischer and Penzoldt in 1887. Avoiding Valentin's progressive dilutions, these investigators sought to determine how much mercaptan and how much chlorphenol must be introduced into the whole mass of air in a laboratory of a certain size in order to give an odor just noticeable to a person entering the room. The walls of the laboratory were perfectly smooth, the floor was of stone, and the equal distribution of the odorous gas to all parts of the room was secured by the motion of fans. The solutions were scattered with a fine spray.[4] Unfortunately, these solutions were alcoholic.

In the same year H. C. Dibbits arrived at a partial determination of the stimulus-limen for the odor of acetic acid. Acetate of zinc is decomposed in the presence of water, and an insoluble basic salt and free acetic acid are formed. Dibbits, during the course of sixteen hours, allowed 60 litres of damp air to pass over a mass of salt which had been freed from water of crystallization, found the loss of weight to be 16.8 mg., and calculated the proportion that the weight of the acetic acid set free must bear to this loss of weight to be $\frac{10}{7}$. As 24 mg. of acetic acid must have been communicated to 60 l. of air, and as the odor was discernible in this air, the stimulus-limen of acetic acid must lie under 0.4 mg. per litre.[5] While the methods of Fischer and Penzoldt and of Dibbits are comparatively accurate, it is obvious that they are impracticable for difference-determinations.

A method employed in 1889 by Ottolenghi for testing the olfactory sensitivity of criminals is a modified form of Valentin's, and is essentially the same as the method recommended by Passy in 1892.

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[1] P. 80.
[2] Valentin: *Grundriss der Physiologie*, p. 515.
[3] Zwaardemaker: *op. cit.*, p. 79.
[4] *American Journal of Psychology*, I, p. 357.
[5] Zwaardemaker: *op. cit.*, p. 84.

Ottolenghi used 12 aqueous solutions of essence of cloves contained in similar bottles in similar quantities. The solutions were graduated from 1: 50000 to 1:100. The subject began with the weakest solution and took the bottles successively until sensation commenced. Passy dissolved a certain weight of odorous material in a given weight of alcohol, mingled a certain fraction of the solution with a given weight of pure alcohol, and so on, until he had obtained a graduated series of saturations. He then put single drops of his solutions into bottles of the same size, and arrived by the method of just noticeable stimuli at an estimate of the stimulus-limen in terms of saturation-strength and the area of his bottles.[1] Ottolenghi's combinations of essence of cloves and water were not true solutions. Passy's results are vitiated by the compensating effect of the odor of the alcohol. Both methods involve an error due to the constant loss of odorous material by the mere opening of the vessels for the subject to smell their contents, by inhalation, and by condensation on the walls of the vessels. Zwaardemaker suggests that fairly satisfactory results might be obtained on Ottolenghi's principle if one (1) employed only solutions in distilled water, (2) made very short inspirations, (3) used very large inhaling vessels, and (4) avoided all odorous substances the vapor of which is easily condensed.[2] Theoretically, if the series of saturations could be minutely enough graduated, this method might be employed for difference-determinations, but practically, the use of many large inhaling-vessels would make it too clumsy.

The first indirect method was invented by Frölich in 1851, three years after Valentin invented his direct method. Frölich gauged the keenness of smell by the distances at which odorous substances could be sensed under uniform conditions. He put up in tightly corked test-tubes such substances as ethereal oils, resins, spices, and musk mixed with starch in such proportions that however different in quality, the odors might be the same in intensity. The subject closed his eyes, the tube was uncorked and moved toward him, and both the distance at which the substance was first sensed and the time at which judgment was passed were marked.[3] Frölich seems, however, to have made little use of his time-estimates. As the odors with which he worked are slowly diffused, the mass of odorous vapor may be thought of as moving with the tube. Yet results based on such a rough hypothesis cannot be very reliable.[4] Moreover, the assumption that odors so unlike in quality are of the same intensity, since they can be just sensed by the same person at the same distance, begs the question of the value of the hypothesis mentioned, and Frölich seems to have had no other means of determining their comparative intensity except guess-work.

Aronsohn's famous method, devised in 1886, though indirect upon the ordinary theory of smell which makes the odorous particles act in gaseous form on the olfactory membrane, must be classed on Aronsohn's own premises as direct. His hypothesis is that odorous particles are in solution when they act on the nerve-endings. This assumption, for which J. Müller is chiefly responsible,[5] is based (1) on the fact that fishes and amphibia have peripheral and central organs similar to the organs of smell in birds and mammals, and (2) on the fact that the nasal membranes are normally covered with mucus,

[1] Pp. 98-99.
[2] P. 99.
[3] Pp. 80-81.
[4] P. 81.
[5] P. 62.

and that the drying of this mucus, as in the first stage of rhinitis, impairs the sense of smell. Tortual and Weber had indeed proved that odorous liquids when introduced into the nose "do not smell," and Weber had also found that the sense is for a time impaired if warm or cold water or sugar and water are poured into the nasal cavities and retained there for a few moments.[1] Aronsohn explained these phenomena by supposing that strong solutions of odorous matter and liquids of foreign temperature if brought in contact with the delicate olfactory membrane must necessarily have a pernicious effect. He found, on the other hand, that very small quantities of odorous substances dissolved in normal saline solutions can be sensed if the mixture, at a temperature of about 40° C., is poured into the nose from the height of about half a meter. Weber had used cologne and water in the proportion of 1 : 11. Aronsohn used oil of cloves, for example, in salt and water in the proportion of 1 : 500. His olfactometric method consisted simply in determining how weak a solution of an odorous substance could be sensed if injected at the temperature proved empirically to be most favorable for its detection.[2] If Aronsohn's premises are correct, not only is his method direct, but the worst difficulties in the measurement of smell-stimuli are eliminated. In criticism of these premises, however, Zwaardemaker points out (1) that aquatic mammals have organs which resemble the organs of smell in land mammals, but are rudimentary, as if useless under water; (2) that the dryness of rhinitis is confined almost exclusively to the Schneiderian membrane and is conjoined with hyperaemia and swelling which obstructs the passage of air; (3) that the cilia of the olfactory cells protrude through the covering of mucus; and (4) that most odorous substances are not at all or are but very slightly soluble in water. Books on the perfume-industry are filled with the discussion of ethereal oils, of spices, gums, and the like. In a room saturated with perfume or tobacco smoke, a bit of cotton wool will take up the odor, while a glass of water will not. Moreover, as Zwaardemaker believes, it cannot be shown that Aronsohn succeeded in filling the cavity which contains the olfactory membrane so entirely with liquid that all bubbles of air were excluded. It is very difficult to drive all the air out of blind pouches.[3]

In 1893, Dr. N. Savelieff in the laboratory of Morokschowetz constructed an olfactometer on a principle entirely different from Zwaardemaker's. There were two flasks of glass, each with two corks. Through one cork in each, the two flasks were connected by a glass tube bent twice at right angles. Through the other cork of one was inserted a glass tube which reached to the bottom. Through this tube a mixture of ethereal oil and water was poured. The liquid did not reach the end of the connecting tube. Through the remaining cork of the second flask, which was filled only with air, was inserted a glass inhaling-tube which divided into a nose-piece for each nostril. The odor of the liquid was weakened by successive additions of water, and the intensity of the stimulus was measured through the proportion by weight which the ethereal oil bears to the water.[4] As Zwaardemaker suggests the method of Savelieff has this great disadvantage, that its results do not stand in simple relations to the real stimulus-intensities. The intensity of the stimulus will vary according to the height of the liquid in the first vessel, and according to the ad-

[1] Weber: *Archiv f. Physiologie*, 1847, p. 351-354.
[2] Aronsohn: *op. cit.*, 1886, pp. 324-332.
[3] *Op. cit.*, pp. 62-66.
[4] *Neurologisches Centralblatt*, 1893, p. 343 sq.[4]

hesion of odorous material in different parts of the apparatus. Savelieff's method would indeed be fairly satisfactory for clinical purposes if real solutions were used instead of mixtures of ethereal oils and water. It is a great disadvantage, however, to begin an experiment by exhausting the sense-organ with a saturated solution.[1]

Section 2. Control in Zwaardemaker's Olfactometric Method of the Factors which Determine the Intensity of the Stimulus.

Zwaardemaker's measurements of the smell-stimulus are in terms of but one factor of the genetic unit,—viz., in terms of the amount of odorous surface exposed. The time for which different extents of surface are exposed is supposed to be kept constant by the regularity of the movement of the hand which manipulates the odorous cylinder. All of these time-values are so small that their variation may well be disregarded.

In 1890, Henry, a French scientist, instituted in the interests of the perfume industry a modified form of Zwaardemaker's method, and took the time values into account. His instrument differs from Zwaardemaker's only in the substitution for the odorous cylinder of a porous paper cylinder, hollow, closed at the bottom, and saturated from a surrounding glass reservoir with the fumes of an odorous liquid. The glass inhaling-tube enters from the top, and the subject raises it with a uniform movement while he is making the inspiration required. Stimulus-intensity is reckoned in terms of the surface of the paper cylinder exposed, and of the time which the odorous vapor has had for diffusing into it since the lifting of the inhaling tube.[2] As for this second factor, by which alone Henry's method differs from Zwaardemaker's, Passy suggests that the time-rate of evaporation of a liquid under a membrane differs from the time-rate of the same fluid in the open air. Henry supposes that the pressure of vapor on the paper cylinder is constant, but on the contrary, since its surface is wholly covered at the beginning of the experiment and is gradually uncovered as the glass tube is raised, the pressure of vapor will constantly decrease.[3] At any rate, Henry's apparatus will not answer for difference-determinations, as it would render procedure in both directions impossible.

Much more serious in Zwaardemaker's method than any error which may arise from irregularity in the subject's movements is the error due to the adhesion of odorous particles in the glass inhaling-tube. These particles may condense on the sides of the tube or, if the substance is soluble in water, may dissolve in the moisture which forms on the inside during inspiration. A correction can be made for adhesion only for the "minimum perceptible," and only for a determination taken with the perfectly dry and clean inhaling-tube and a saturated porcelain cylinder. It may be made as follows: Let the length of the inhaling-tube ordinarily used be x and let a be the value of the stimulus-limen as found with it. Then let a

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[1] *Op. cit.*, pp. 100-101.
[2] *Comptes rendus de l'Academie des Sciences*, Feb. 9, 1891.
[3] Zwaardemaker: *op. cit.*, p. 94.

shorter inhaling-tube of the same diameter and the length y be pushed for about 2 mm. into the odorous cylinder. Through the other end of this cylinder, which is usually the movable part of the instrument, let a third tube of the same diameter be pushed. By moving this third tube backward and forward, the extent of odorous surface exposed to the air is varied. Let the stimulus-limen found under these conditions be b. Then $a - b$ will be the difference in the stimulus-limen made by the adhesion of odorous particles to a tube of the length $x—y$. The correction to be made for adhesion to a tube of the length x will be as much greater as x is greater than $x—y$. If cylinders of solid odorous substances be used, this correction cannot be made, even for the stimulus-limen, since it is so exceedingly small. It is impossible, moreover, to take many determinations even of the stimulus-limen in an hour with a perfectly dry and clean tube. As for the difference-limen, it is both theoretically and practically impossible to make the adhesion-correction, for to know how much greater for sensation a given stimulus is than the liminal stimulus, one would have to know beforehand that Weber's law applied to that particular olfactory quality, and what the exact value of $\frac{\Delta r}{r}$ for the quality was. The effect of adhesion, in the first inspiration or at least in the very first few inspirations, is to decrease the strength of the stimulus, but after the first or at most after the second or third inspiration, the effect is rather to increase the strength of the stimulus, since the odor from the matter adhering to the inhaling-tube more than compensates for the loss of the odor of the matter which continues to adhere.

The tube must be carefully dried after it has been washed, and the subject must be trained not to breathe back into it. Yet on a damp day, the moisture left on the inside of the tube by the inspired air is no inconsiderable source of error. Bunsen computes the possible thickness of such a layer at 0.00101 mm. If a glass tube is 15 cm. long and 5 mm. wide, the area of its bore will be 23.57 qmm. This would make the weight of a layer of moisture of the thickness given by Bunsen 2.38 mg. If the odorous substance is in aqueous solution, this moisture may be left out of account, but if no moisture comes from the cylinder itself, it may vitiate the results of the experiment. Since the dampness of the air varies from day to day, this error cannot well be corrected.[1] All that one can do is faithfully to take the barometer-readings in the hope of finding in them possible explanations of erratic judgments. The experimenter must be careful to cool the inhaling-tube after dry-

[1] Pp. 124-125.

ing it over the spirit-flame, not only on account of the risk of distracting the subject's attention with a warm tube, but on account of the danger of heating the inside of the odorous cylinder.

Since the source of the odorous vapor is connected with the subject's nose by a tube of known length, the diffusion of the matter is, outside of the body, obviously under complete control.

The subject's breathing is, indeed, a seriously variable element, but its variation is by no means the greatest practical drawback to the method. Sniffing must, of course, be watched for and peremptorily forbidden. The mere expansion of the nostrils does not increase the intensity of the odor as it does under ordinary circumstances, but rather decreases it, since the field of smell is artificially limited, and the widening of the entrance to the nose simply increases the amount of air which dilutes the odorous gas. Under ordinary circumstances, as we have seen, the more rapidly one breathes, the stronger the odor one will get. If one uses the olfactometer, this is not true. Since the diffusion-rate within the cylinder is constant, increased rapidity of breathing will increase the degree in which the odorous particles are diluted with air on their entrance to the nasal passages. Thus, the more slowly one breathes, within a certain limit, the stronger the smell one will get. The air must be drawn in with enough force to carry part of the current above the lower turbinal bone. If the air simply takes the straight path to the choana along the floor of the nasal cavity under the lower turbinal bone, there will be no smell. Zwaardemaker believes that each subject with a little practice will discover for himself the best rate of breathing for obtaining the strongest smell from a given stimulus, so that, in a manner, the breathing rate will be self-regulating.[1] Our own experimental results seem to bear out this conclusion. In Section I of Chapter III, each subject's mode of breathing is noted, but its peculiarities can scarcely be traced in the numerical results. The inability of most of the subjects to arrive at difference-determinations with one inspiration must, of course, have aggravated the adhesion-error. Henry regulates the breathing of his subjects by putting about the chest a belt which allows only a certain expansion. Such an appliance must, however, have the effect of distracting the subject's attention and making the breathing unnatural. Following Zwaardemaker's example, we did not even stop the nostril not in use. The inhaling-tube was thrust into the forward[2] half of the nostril to the depth of half a centimetre.

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[1] Pp. 86-87.

[2] A substance pressed against the back of the nostril can hardly be smelled at all, as its vapor will take the direct path to the choana.

We may say, then, that the most unsatisfactory features of Zwaardemaker's method are (1) the adhesion-error, and (2) a tendency which the subject, if he manipulates the odorous cylinder, has toward judging in terms of hand-movement. This difficulty will be discussed in another place.

While the intensity of the stimulus depends in the case of any sense upon the condition of the peripheral organ, no sense-organ is so likely to vary either through obstruction or through exhaustion as is the organ of smell. Let us now consider the variations from the normal condition to which this organ is most subject.

Section 3. Anosmia and Hyperosmia.[1]

Whether pathological or non-pathological in origin, anosmia is of three sorts,—respiratory, essential or toxic, and nervous. Respiratory anosmia is due to obstruction of the nasal passages, from asymmetry of the nasal skeleton, from hyperaemia of the respiratory or Schneiderian membrane, or from accumulation of mucus. Toxic anosmia may be due to poisons in the inspired air,—a form not yet investigated,—to injurious fluids introduced directly into the chamber containing the sense-epithelium (as in Aronsohn's experiments), to poisons, such as morphine, pulverized and blown into the nose, or to certain forms of blood-poisoning, such as chronic nicotine-poisoning. The anosmia of smokers cannot be wholly attributed to their catarrh, though a light, acute nicotine-poisoning does not seem to produce a loss of smell. Nervous anosmia may be congenital,—*i. e.*, due to imperfect development of the olfactory vesicle in the brain,—or may be senile,—due to degeneration of some of the nervous elements which condition the sense,—or may be due to exhaustion of the olfactory nerve, or to dryness of the epithelium. If we rule out exhaustion, we may say that respiratory anosmia is vastly more common than toxic or nervous. The more peripheral parts of every sense-organ are more subject to injury and disease. Thus, the muscles and lenses of the eye give much more trouble than the retina and the optic nerve. In the case of smell, the sensory epithelium is well protected by its secluded position.

As to hyperaemia of the respiratory mucous membrane, its blood supply is controlled much more by the exigencies of breathing than by those of smell. It is largely under the sway of local reflexes. The fibers of the trigeminus which ramify through it are closely connected with fibers of the sympathetic nervous system. Too profuse secretion of mucus is the most common mechanical hindrance to smell. On the other hand,

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[1] Pp. 136-165.

too small a secretion has a disastrous effect on the sense-epithelium. It seems that the tiny hairs of the rod-cells refuse to do their work if they become dry. The action of all the mucous glands of the nose may be increased by injecting strychnine, and decreased by injecting atropin into the membranes. Too much atropin, however, produces irritation and a flow of tears.

Hyperosmia may also be respiratory,—due to certain asymmetries of the skeleton or to anæmia of the respiratory membrane,—or toxic, or nervous. In hysterical subjects, hyperosmia is common. Anæmia of the respiratory membrane may be produced by smelling such substances as cocoa-butter, or cedar-wood, which rather powerfully affect the trigeminus.

The two forms of anosmia, which vary in the same subject from day to day, are respiratory anosmia from obstruction of the nasal passages by mucus, and nervous anosmia from exhaustion. It is possible at any time easily to discover whether the nasal passages are obstructed or not. The test can be made by exhaling on a concave metal mirror held at the level of the mouth. The clouds of condensed vapor give the true shape of transverse sections of the breathing-cones. They are divided from each other, and if the nasal passages are in a normal condition, they are symmetrical, and broader than they are long. As they pass away, they should each divide into an antero-medial and a postero-lateral division of about the same size. As divided, the spots should still be roughly symmetrical. The division is due to the projection of the "triangular cartilage" and the lower turbinal bone from the side wall of the nose. This division of the air current occurs in all mammals.[1] Pathological alterations in the mucous membrane of the nose and asymmetry of the nasal skeleton may alter the size and shape of these divisions, but rarely prevent them from appearing. The antero-medial division alone represents the current of air which passes above the lower turbinal bone. The form and position of the field of smell in an ordinary inspiration, therefore, corresponds roughly with this division, and would do so exactly if it were not for the slight difference in the course of the currents of inspired and expired air.[2]

The influence of exhaustion is more insidious. It varies from subject to subject, from substance to substance, and from one intensity of a substance and one general condition of a subject to another, so that numerical corrections are out of the question. Fortunately or unfortunately, the effects of adhesion and exhaustion are for the most part opposite. This

[1] P. 73.
[2] Pp. 73-74.

opposite influence makes one's numerical results more nearly correct than they would otherwise be. On the other hand, it makes the exact influence of each source of error more difficult to read from the figures. Yet it is not particularly difficult to detect the effect of the exhaustion when it is at all marked, and to exclude the most unreliable determinations. In our experience of thirteen different subjects, complete or marked anosmia from exhaustion, if it occurred at all, usually came on very suddenly.

Section 4. Psychophysical Methods Employed.

Before difference-determinations were made at all, the stimulus-limen was usually found as accurately as possible for the substance and subject concerned. The subject, starting with the end of the odorous cylinder even with the end of the inhaling-tube, moved the cylinder outward until he obtained a smell. If this smell seemed to him more than liminal, he moved the cylinder back for a short distance, and continued to move backwards and forwards until he had satisfied himself as to the point at which he obtained a just noticeable sensation. The method of moving steadily in both directions,—from a point considerably below to a point just above the limen, and from a point considerably above to a point just below the limen,—was tried, but was abandoned. It is often impossible, on account of adhesion in the tube or in the nasal passages, or on account of memory after-images, or cumulative stimulation, to move from a point of intensive stimulation to a point at which sensation entirely disappears. Memory after-images certainly occur. The existence of true after-images of peripheral origin has not been proved in the case of smell.[1]

The only difference-determinations for smell, so far on record, are a few which Zwaardemaker performed for yellow wax and vulcanized rubber. The method which he employed, and the method which so far seems practicable, is Fechner's rough and simple method of just noticeable differences. One gives the subject a standard stimulus, and then after an interval, which one makes as nearly uniform as possible, a second stimulus which is appreciably greater or smaller. He himself then moves the cylinder until he makes the stimulus just greater or just smaller than the standard. When in the neighborhood of the stimulus, he moves back and forth as he likes, until he has satisfied himself of the accuracy of the determination. Thus, as there is near the limen procedure in both directions, the method may be classed as a gradation-method. The interval between the two stimuli averaged in our experiments 2½

[1] P. 260.

seconds with the standard olfactometer, and 5 seconds with the fluid-mantle olfactometer. With the small olfactometer, it was never less than 2, and almost never greater than 4 seconds. It was ordinarily 2. With the large olfactometer, it varied from 4 to 6 seconds. The difficulty in manipulating the large olfactometer more quickly will be described in another place. The interval between determinations was much more variable. It was usually about a minute, except when the tube was cleaned. Our determinations were broken into short series in which Δro and Δru were found alternately. The series were divided from each other by the necessary cleanings of the inhaling-tube. With some substances, we washed and dried the tube after every 8 determinations, wiping it out with dry absorbent cotton in the middle of the series. With other substances, we washed and dried it at the end of every 4 determinations. It took about a minute to give the tube a dry wipe, making the interval between half series about 2 minutes. After practice, it took about 3 minutes to wash, wipe and dry the tube, making the interval between series about 4 minutes. These time estimates are all rough. We were not intent on time-determinations; the subject had often incidental remarks to make on his own experiences; and there were various untoward accidents,—water spilled, tubes broken, wire dropped, etc. The subject used his two nostrils alternately; all our records were kept for the two nostrils of each subject as for two different persons. We changed the order of determinations in successive series that exhaustion and adhesion might equally affect Δro and Δru for the right nostril and for the left. For example, 4 series might run thus:

(1) $\triangle ro$ f. R. N., $\triangle ro$ f. L. N., $\triangle ru$ f. R. N., $\triangle ru$ f. L. N.
(2) $\triangle ru$ f. L. N., $\triangle ru$ f. R. N., $\triangle ro$ f. L. N., $\triangle ro$ f. R. N.
(3) $\triangle ru$ f. R. N., $\triangle ru$ f. L. N., $\triangle ro$ f. R. N., $\triangle ro$ f. L. N.
(4) $\triangle ro$ f. L. N., $\triangle ro$ f. R. N., $\triangle ru$ f. L. N., $\triangle ru$ f. R. N.

With the standard olfactometer, after some practice in cleaning the tube, we took usually 32 determinations in an hour; with the fluid-mantle olfactometer, 24. It was not worth while to take more even if there was time, as the effect of exhaustion became too marked. Fortunately, the odors of the solids used with the small and easily handled olfactometer, were less exhausting than the insistent smells of most of the solutions.

With an unpracticed subject, we used one standard a day. With a practiced subject, we took determinations first with a weaker, then with a stronger standard on the same day. If the substance was very exhausting, we worked first with a weaker, then with a stronger, then with a weaker, then with a

stronger standard. The subject was always warned of a change in the standard.

Two grounds of objection to the method of just noticeable differences are mentioned by Wundt. They are the haphazard choice of the more intensive stimulus, which may light upon a stimulus unnecessarily large, and thus weary the subject's attention and sense-organ unnecessarily, and the irregularity and immeasurability of the moving back and forth in the vicinity of the difference-limen,—the "Tatonnieren." It should be noted, however, that as exhaustion increases during the act of determination, $\triangle ro$ would always be too large and $\triangle ru$ too small, were it not that adhesion has a precisely opposite effect, which is increased by the time-error. Thus, there is really a rude double cancelling of errors.

The true method of minimal changes involves great practical difficulties if applied to difference-determinations with Zwaardemaker's olfactometer. On account of the adhesion in the inhaling-tube, either two olfactometers must be used, and both inhaling-tubes cleaned after every comparison of two stimuli, or only such substances must be used as are insoluble in water and do not condense on the inner surface of the inhaling-tube. Zwaardemaker tried the method with vulcanized India-rubber, and believes it to be practicable for this substance.[1] We, too, tried it with the tube of red vulcanized India-rubber sent from Holland, and obtained very satisfactory results. (See Table VIII.)

We also tried a combination of the two methods mentioned. Giving the subject a variable stimulus objectively equal to the standard, we bade him make it subjectively equal,—for it would tend to seem subjectively less from the effect of exhaustion,—and then after pausing to let us take the reading, to make it subjectively just greater than the standard. Then he was directed to make a variable stimulus very appreciably greater, just equal subjectively. Next, after making an objectively equal stimulus subjectively equal, he made it subjectively less. Lastly, he made an appreciably weaker stimulus subjectively equal to the standard. Some of the results obtained by this method are given in Table VII. They are arranged in connection with results obtained for the same subject, substance and standard by the method of just noticeable differences. The uncertainty of a method in which the subject exhausts an already wearied organ by hunting for subjective equality before proceeding to the determination proper, is obvious. Therefore, the two sets of results tally surprisingly well.

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[1] Pp. 189-190.

With any form of the method of just noticeable differences in which the subject himself alters the stimulus of comparison, there is liability to serious error from the subject's inclination to judge in terms of movement. When he has found that a certain hand-movement has made the stimulus of comparison just noticeably greater or less than the standard, he will expect the same movement to make it just noticeably greater or less again. He will be all the more tempted to judge in terms of hand-movement from the fact that he has been all his life forming estimates of space in terms of the sensations produced by movement, and has probably never thought of taking pains to compare the intensity of two odors. This tendency varies much in different subjects. Its presence may be suspected when the mean variation of a series is very small. Fortunately, it acts in such a way as rather to conceal the operation of Weber's law, if applicable, than to make it appear applicable if it were not. If, for example, one finds Δr to be 5 mm. for a standard of 20 mm., and by repeating the series of movements, obtains the same value of Δr for a standard of 40 mm., $\frac{\Delta r}{r}$ will be $\frac{1}{4}$ in the one case, and $\frac{1}{8}$ in the other.

As a matter of fact our results offer evidence for the law which is strong to an almost suspicious degree. Yet it is not probable that a trained subject would, or that an untrained subject could deliberately alter his movements, when the stand- was varied, so as to keep the value of $\frac{\Delta r}{r}$ approximately the same, and it is absolutely impossible that twelve subjects out of thirteen should all do so. Such a procedure would argue a miraculous combination of psychophysical knowledge, accurate memory, industry and malice.

We also made some attempt to test the applicability of the method of right and wrong cases. At the time we tried it, which was early in the course of our experiments, we found it utterly impracticable. The fact that more than half the mistakes were made in thinking the second stimulus weaker than the first or equal to it, would indicate that exhaustion was the disturbing factor. Since, however, the subject seems genuinely to recognize the stimulus of comparison in the gradation-methods as greater or less than the standard, it is probable that the difficulty with the method of right and wrong cases is largely the utter confusion it produces in his mind. Most persons are not used to smelling attentively and have to "learn" a given smell-intensity.

Chapter II. Apparatus and Materials.

Section 1. The Standard and Fluid-Mantle Olfactometers.

In our experiments, we employed the single "standard" olfactometer and a double form of the "fluid-mantle" olfactometer. Both instruments were supplied from Utrecht. The sliding tubes used with the standard or small olfactometer were formed of the odorous material itself, and covered with an outer tube of glass. Porcelain cylinders, saturated with odorous solutions, and fitted into larger glass tubes, have been largely used by Zwaardemaker in connection with this simple instrument. We, however, used the porcelain cylinders only with the large or fluid-mantle olfactometer. We shall reserve the consideration of the preparation of the odorous substances to the next section. Here we shall describe the screen and inhaling-tube of the small instrument, and all the appurtenances of the large instrument, except the odorous solutions.

I. Standard Olfactometer. The glass inhaling-tube has a total length of 15 cm. and a bore of 5 mm. The glass varies in different tubes from 1 to 1½ mm. in thickness. The portion which curves upward to fit into the nostril is never more than 1½ cm. long. Zwaardemaker says that the angle of the bend seems to make no difference with the results of the experiment. He himself makes it a right angle, but Reuter makes it an angle of 40 degrees.[1] A metal sleeve carrying a raised bead at the edge towards the bent end of the tube and buttoning into a metal ring in the center of the small wooden screen is fastened to the tube in such a position as to allow 10 cm. to project beyond the screen. This portion is graduated into twenty divisions of 5 mm. each. The securing of the metal to the tube is a serious problem in practice. We were able to find neither odorless glue nor cement which would withstand the constant washing of the tube, and the drying over the spirit-flame, a performance which must be repeated from four to a dozen times in a single hour. We finally solved the difficulty for ourselves by pasting with freshly dissolved gum arabic a strip of paper to the tube, and working the metal ring down over it, where it fitted so tightly as not to be removed without a process of soaking. The graduated tubes can be easily duplicated by any glassware firm.[2] They are so frequently broken in cleaning by an unpracticed operator, that no extended course of experiments should be undertaken without laying in a stock of them.

The screen is a square bit of cherry wood,—7½ cm. broad by 10 cm. high by 1 cm. thick,—furnished with a handle and coated with varnish which is supposed to be odorless. The screen must, however, be freely exposed to the air, and when new, must be well sunned, or it will have a decided smell of its own. Its double purpose is to serve as a handle, and to protect the nostril not in use from the odor of the sliding cylinder. The subject in making his determination holds the handle of the screen in his left hand and moves the cylinder with his right.[3]

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[1] P. 104.

[2] Messrs. Eimer and Amend, of New York, courteously duplicated for us all of our imported tubes.

[3] The standard olfactometer can be made in any laboratory. See the

II. Fluid-Mantle Olfactometer. In this instrument, the constant saturation of the hollow porcelain cylinder is secured in the following manner: A section of wide glass tubing is secured between two circular and cork-lined end-plates of metal. One of the metal plates,—that which when the instrument is adjusted is nearer to the subject,—is furnished with three equidistant rods, inside of which the disks of cork and the glass tube fit. The three rods terminate in three screws with detachable heads. The screws pass through holes in the other metal plate. The plates are bored at the center to circular openings, 8 mm. in diameter, which coincide with the bore of the enclosed porcelain cylinder. The cylinder itself, which has exactly the length of the glass tube,—10 cm.,—is held in place simply by the pressure of the end-plates. The glass inhaling-tube passes through the screen into the bore of the cylinder. The odorous solution is put into the space between the cylinder and the glass tube with a pipette through one of two holes, 2 mm. in diameter, which are left one in each of the two metal plates, and closed with cork-lined screw-heads. It would be better if there were two of these holes in each plate, for it is extremely difficult to force a sluggish liquid, such as glycerine, against the pressure of the air into the space around the cylinder. If the rubber of the pipette is flaccid, it becomes almost impossible.

The "shells" thus constructed for mantling the cylinder with liquid, are mounted in a horizontal position on a wooden table,—27.7 cm. long by 16.4 cm. wide,—which can be adjusted to the required height above a heavily leaded base. Each of the shells can be moved to and from the observer along a way of hard wood. The rack and pinion movement is governed by milled heads,—diameter 2½ cm.,—projecting from the table to right and left within easy grasp of the subject's hand. A scale and pointer enable the observer to determine how far the cylinder is moved.

The inhaling-tubes are made with the same bore and of glass of the same thickness as the graduated tubes used with the standard olfactometer. Those sent from Holland turn, one to the right and the other to the left before curving upward to be inserted in the nose. The metal sleeves, within which the tubes are cemented, do not bolt into the holes in the screen, but flare off each on its outer side into flat fan-shaped pieces of metal, which are screwed to tally with a mark on the screen. We made no experiments with these tubes, but used instead tubes of the same bore and thickness of glass, either with a somewhat shorter upright, or with but one curve. The tubes with one curve are precisely like the inhaling-tubes of the standard olfactometer, except that the part which extends through the screen is longer and is not graduated. It is a mistake to use two-jointed tubes at all, unless both nostrils are to be used, as in compensation-experiments. The extra curve seems to make no difference in the results, but it makes the tubes much harder to clean. The total length of our two-jointed tubes was 18½ cm., and that of our one-jointed tubes, 17½ cm. 11.3 cm. of every tube used must project beyond the screen. We fitted our tubes into hollow plugs of cherry wood turned to order in the shape of corks, so as to pass easily into the holes of the screen, and

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directions given in Sanford: *Experimental Psychology*, p. 371. Scripture's blotting-paper olfactometer as, made by Willyoung, is rendered useless by the vulcanized India-rubber of the inhaling-tubes. We substituted for the inner glass-tube, rubber-tube, and nose-piece, a glass tube bent at right angles and expanded into a nose-piece at its upper end. The dimensions of this tube, however, make it very breakable, and it is quite impossible to clean it except by blowing through it.

to fit tightly when pushed home. To keep the tubes themselves from slipping backwards and forwards in the plugs, we gummed strips of paper to the glass at the edge of the wood. Lumps of these strips will continue to adhere even after many washings. These home-made substitutes for the heavy metal attachments are very serviceable.

We should advise all who purchase the instrument to strengthen the table with metal cross pieces on its under side. The upward warping, which is inevitable, narrows the ways and throws the inhaling-tube out of alignment with the porcelain cylinder. The result is a stiff movement of the rack and pinion on the one hand, and a perpetual breaking of inhaling-tubes on the other. Moreover, if the warping has gone far, the whole table is liable to split. We have also found it necessary to shave the edges of the wooden blocks which carry the shells, and to reduce the friction caused by two spring-brakes placed alongside of the ways. It would be much better if the carrying blocks were moved with cranks, rather than by the milled heads. The exertion necessary to turn the screw and the chafing of the hand by the milling are distracting to the subject's attention. Moreover, the intervals when the experimenter is turning the head to give the stimulus of comparison are undesirably long. Great care must be used in the selection of any oil which is applied to the instrument. We once used clock oil, and afterwards had extreme trouble in eradicating the odor.

The porcelain cylinders for these olfactometers are made by Hooft and Labouchere in Delft, and composed of pure kaolin. They must be kept continually immersed in water, and this must be removed at least daily to minimize the odor of the clay. They must not be dried before they are introduced into their glass coverings. The ends are perfectly smooth, and are glazed for use with the standard olfactometer. The outer and inner surfaces remain porous. All the cylinders used, whether made of porcelain or of the fragrant material itself, have a length of 10 cm., and a bore of 8 mm., so as to slide easily along the inhaling-tube, and to cover, in case of the standard olfactometer, the graduated portion of the tube lying beyond the screen. The external diameter,—counting the thickness of the protecting shell of glass, when present,—varies from 14 to 16 mm.

Section 2. Preparation of Odorous Materials.

In Table VI (Chapter III, Section 2) the odorous materials are arranged in their order according to Zwaardemaker's scheme of olfactory qualities. We shall here describe them in groups according to their mode of preparation. We shall consider first the preparation of the tubes of solid odorous matter, and afterwards discuss the solutions used to saturate the porcelain cylinders.

I. Preparation of Odorous Substances Used in Solid Form. The solid odorous materials from which tubes or hollow cylinders were prepared were vulcanized India rubber, black, red, and gray; cedar, rose-wood and musk-root; Russian leather, yellow wax, paraffine, glycerine soap, mutton-tallow, cocoa-butter and solid oil of mace, asafœtida, gum benzoin, tolu balsam, and a combination of gutta-percha and gum ammoniac in equal parts by weight. Tubes of red and black India rubber, and of gutta-percha and gum ammoniac came with the standard olfactometer from Utrecht. All the other cylinders, and a second tube of gutta-percha and gum ammoniac, were home-made. It is necessary that all such cylinders should be fitted into glass tubes

of the same length in order that no odor from their outer surfaces may pass around the screen.

India rubber has three great qualifications for use in experiments in smell. (1) It can be smelled for a long time by most subjects without blunting the organ; (2) its odor is not easily obscured by other odors, and (3) adheres comparatively little to the inhaling-tube. Two of our subjects (*C.* and *Sh.*), however, complained more of smarting in the nose when using rubber than when using any other substance. The age and mode of preparation of different sorts of rubber, and the amounts of sulphur in them, make some difference in the quality and slight differences in the intensity of the smell. The intensity, is, on the other hand, virtually the same at all degrees of temperature between 13° and 30° C. The cylinder may be prepared by cutting 10 cm. from a rubber tube with a bore of 8 mm., and working it into a glass tube of the same length. The rubber must be clean and new, and, in particular, must never have come in contact with illuminating gas. Although the odor of the rubber when fresh is not easily disguised by other smells, yet the substance easily loses its own odor and takes that of other substances. An inhaling-tube or the broken fragment of one should, therefore, be left in the cylinder so as to cover its inner surface when not in use. Such tubes must never be allowed to lie about unprotected on the shelves of a wooden cupboard. If not sealed by containing the inhaling-tube, they should be rolled up in clean glazed paper and shut up in a jar by themselves.

Our cedar and rose-wood cylinders were turned to order. A block of wood 2½x2½x4½ ins. will make four of these tubes. Each was held in its place in the outer tube of glass by a small bit of "instant crockery-mender" applied to the wood before putting it in. The fit is so tight that the odor of the paste cannot escape. These cylinders also are very liable to lose part of their odor, and should be carefully protected. Messrs. McKesson and Robbins, of New York, furnished a single piece of musk-root large enough to make two cylinders. One crumbled in the turning, but the other broke evenly around the circumference into two sections, which were pushed so tightly into a glass tube as to stay in place of themselves. The crack was almost invisible, and as it was 6 cm. from one end of the tube, it did not render the cylinder really defective. From the Russian leather,—which was genuine, and not the "Russian leather" of America, which is tanned with birch instead of sandal wood,—a piece 24 mm. wide and 10 cm. long was cut, and was fitted into a tube so as exactly to cover the inner surface. Cylinders may be prepared in the same way from India rubber sheeting.

The other substances were all melted and moulded. The glycerine soap was Pear's, the mutton fat employed was fresh from the butcher's, the cocoa-butter, paraffine (the kind used by histologists), gum benzoin and gum ammoniac were such as can be bought of any retail druggist. We obtained of McKesson and Robbins "solid" oil of mace and the pure juice of asafœtida done up in small tin cans, and also a quantity of gutta-percha in narrow fibrous sticks or slabs, and of tolu balsam entirely freed from impurities. For the outside mould, the permanent glass shell must, of course, be used. The glass tubing was cut beforehand in our case into lengths of 10 cm., and these moulds were corked at one end, so that the tube of odorous matter was never quite so long as its shell. For the inside mould, we used an inhaling-tube, or the long straight part of one which had broken at the curve. The tube may be kept upright by digging a hole for the end of it in the cork. This end should be plugged to prevent the liquid from working up into the tube, through which it is sometimes necessary to pour

warm or cold water. All the odorous substances in this group were melted in a water-bath. We crumbled or shaved them into a small beaker, which we floated by means of a ring of cork in a large beaker of water over a Bunsen burner. We tried to melt the gums in a sand-bath, but succeeded only in charring them. The mass which we obtained by melting the gum ammoniac and gutta-percha together was of lighter color than that sent from Holland, and was not entirely free from the fibres of the gutta-percha. It was spongy and easily moulded by the fingers into any desired shape. The soap, paraffine, cocoa-butter and tallow are readily manipulated. They solidify in a very few moments if the outer tube is immersed in cold water, and the removal of the inner mould presents no difficulty. Tubes of these materials were kept all the summer in a room of which the temperature occasionally rose to 94° F., and sustained no damage by the heat. The tubes of soap, however, sometimes shrivel in a few days independently of the temperature. The longer the paraffine is heated the stronger the odor. Zwaardemaker succeeds in giving it an odor as strong as that of tallow or musk-root. We did not try heating it longer than an hour and a half, and our paraffine tubes gave the weakest of all our scents. Tubes of tallow are easy to make and to keep, and do not exhaust the subject's sense-organ to any appreciable extent, and are therefore especially to be recommended.

The oil of mace has a consistency like that of table-butter. It melts rapidly, and solidifies almost instantly when the outer mould is plunged into ice water, but tends to stick to the inner tube, and to come out with it in perfect shape. To remove the inner tube by itself, we filled it with ice water, and then hastily poured a little hot water over the outer mould. When once made, the mace tubes should be kept in a cool place, and the jar in which they stand should not be set on end. While they are in use, they must be grasped only with the tips of the fingers, and must be cooled every few moments with ice or snow. The juice of asafœtida, when pure, never becomes solid enough to be moulded. We poured small quantities of it, when melted, upon a mass of pulverized carbonate of magnesia, and worked the two materials together with our fingers, as one works flour into a very soft dough. We put lumps of this mixture into an outer mould, heated it in the water bath for a few moments, and then forced the inner tube down through the mass as nearly parallel with the outer mould as possible. After many attempts, we succeeded in making several satisfactory cylinders. Their odor, in spite of the adulteration of the asafœtida, is only too strong.

The gums never become very liquid in melting, and they solidify almost instantly when removed from the heat. We found it difficult to pour the gum benzoin, and impossible to pour the tolu and the mixture of gutta-percha and gum ammoniac, into the space between the inner and outer moulds. We poured this mixture and the tolu into the outer tube when empty, and then forced the inner tube into its place, as in the case of the asafœtida. When the fragrant substance is a gum, this inner tube must be greased. We coated it rather thickly, but evenly, with lanolene, which is as nearly odorless as grease can easily be found, and which evaporates quickly. All these tubes of gum retain their odors well, but the tolu is likely to melt out of shape in a hot room.

Before these cylinders are used, the section of odorless substance exposed at the outer end must be covered. We employed a little ring or cap of glazed paper gummed to the surface. Even with this precaution, the odor of the asafœtida, mace, butter and Russian leather, is quite apparent when the instrument is closed by pushing the odorous tube

as far in as possible. It apparently proceeds from such space as there is between the inside surface and the inhaling-tube. The inhaling-tube, on the other hand, must not fit too closely in the inside of the odorous tube, for if it does, the subject will be able to move it only in irregular jerks, and it will, moreover, scrape off shavings from the inside surface of a cylinder of soft material, such as asafœtida or oil of mace. When it is used with the Russian leather, a bit of paper may be gummed around it to make it fit somewhat more closely. Even this, however, does not keep the smell of the leather from making itself apparent in the space from which one breathes through the tube. We attempted to find "negative stimulus-limina" for the troublesome substances, in the following manner: We used a graduated inhaling-tube 4 cm. longer than the ordinary one, and adjusting the cylinder over the 10 cm. nearest the screen, moved out to find the limen. The device was not successful. The odor still diffused itself through the space from which the air was drawn. All the determinations of difference-limina for these substances involve a constant error,—namely, the addition of an increment, which we have no means of measuring, to every stimulus represented on the tube.

II. Preparation of Odorous Substances in Solution. Of the odorous substances used in solution, the caryophylline, citral, vanilline, coumarine and heliotropine were among the "De Laire Specialties," and were, with the ethyl butyrate, tincture of musk, and oil of camphor, the gift of Messrs. Dodge and Olcott, of New York. "The De Laire products," writes a representative of Dodge and Olcott, "are not an embodiment of the simple chemical formulas suggested by their names. They are compounds after secret recipes, and their names denote only the odor or flavor or other quality which it is claimed they reproduce or imitate. De Laire's caryophylline, for example, is not the caryophylline of your chemical formulas, a distinctly isolated aromatic principle, but a preparation, having doubtless as its base one of the clove-oil products, which is intended to supply the perfumer with the bouquet of the clove-pink." We have retained the De Laire spelling of their own specialties. The chemical formulæ of butyric ether, valerianic acid, allyl sulphide, and pyridin are, respectively, $C_2\ H_5 . C_4\ H_7\ O_2$, $C_5\ H_{10}\ O_2$, $(C_3\ H_5)\ S$, and $C_5\ H_5\ N$. The butyric ether used was a commercial product, but the valerianic acid was obtained at the chemical laboratory of the University, and the allyl sulphide and pyridin, as well as the oil of anise, were had of the Theodore Metcalf Company, of Boston.

Our solvents, mixtures, and concentrations were as follows:

Oil of camphor in liquid paraffine, a mixture,	1:500
Caryophylline in pure glycerine, a true solution,	1:500
Oil of anise in liquid paraffine, a mixture,	1:166⅔
Valerianic acid, in water, a true solution,	1:1500
Ethyl butyrate, " " "	1:1000
Citral, in liquid paraffine, " "	1:500
Vanilline, in pure glycerine, " "	1:125
Coumarine, in liquid paraffine, " "	1:1000
Heliotropine, in liquid paraffine, " "	1:125
Natural Musk, the ordinary alcoholic tincture, in water, a mixture,	1:125
Allyl Sulphide, in liquid paraffine, a true solution,	1:1000
Pyridin, in water, a true solution,	1:500
Laudanum, the ordinary alcoholic tincture, a true solution, unmixed.	

Some of the musk was of course precipitated by the addition of so much water, and floated about in dark brown specks, a state of affairs anything but desirable.

We are aware that all the concentrations are startlingly high. We could not, however, use lower concentrations if we were to fix our standard-stimulus in two places on the scale. With a few exceptions, our stimulus-limina were much higher than those given by Zwaardemaker as normal. These facts will be noted later in detail. Zwaardemaker recommended vanilline in glycerine in the concentration of 1:1000 and coumarine and allyl sulphide in paraffine in the same concentration as especially well fitted for difference-determinations. We did use the coumarine and allyl sulphide in these concentrations, but most of our subjects obtained no odor whatever from the vanilline at 1:1000, and in no case did the stimulus-limen fall for both nostrils below 36 mm.

For coumarine, heliotropine and tincture of musk, stimulus-limina were found in a satisfactory manner. With all the other substances, an odor was apparent when the pointer of the fluid-mantle olfactometer stood at zero. The odor, undoubtedly, came from the space between the inhaling-tube and the inside of the porcelain cylinder, as great pains had been taken to wash away every drop of liquid from the metal plates. It is almost impossible so to adjust the inhaling-tube that it will not scrape against the clay at some point, and to paste paper around it would be out of the question, since the paper would continually rub and wipe the odorous surface. The odor was apparent 4 cm. from the end of the ordinary inhaling-tube when the cylinder was supposed to be sealed. All the determinations of difference-limina for these substances also are, therefore, subject to a constant error, but not so great an error as occurs in the results for the troublesome solids with the exception of Russian leather. The odor of the solutions when the instrument was closed was usually barely liminal.

When water was used as a solvent, it was, of course, distilled. The measuring-glasses and the bottles used should be rinsed well with distilled water, or at least with water which has been freshly sterilized by boiling just before the liquids are poured into them. An aqueous solution becomes unfit for use if long exposed to the light. Zwaardemaker advises that the fluid-mantle of the porcelain cylinder be changed every two days. We usually not only changed the mantle, but made a fresh solution, as often as this. It is safe to use the same glycerine or paraffine solution for days or even some weeks. The glycerine is much more difficult to put into the receptacle than the paraffine, and for citral and caryophylline it is not so able a solvent. It is difficult, however, to obtain and keep liquid paraffine quite free from a slight odor, somewhat pungent and somewhat like that of vaseline. Alcoholic solutions are, of course, more or less undesirable, as we have noted before. If $\frac{\triangle r}{r}$ were known to bet he same for all qualities, there would be no objection to using such solutions, but to assume that it is, is to beg one question at issue. We could not manage the musk and the opium, however, in any other form.

Section 3. Other Arrangements and Appliances.

For cleaning the inhaling-tubes, one needs a funnel of which one end is small enough to fit into the bore; two small light vessels,—tin cups are best,—for pouring water back and forth through them; a roll of absorbent cotton; a piece of pliable brass wire; some listerine; and a small alcohol lamp. After a tube is washed, it must be wiped inside and out with absorbent cotton before it is dried more thoroughly over the spirit-flame, else it will break. We used listerine occasion-

ally as a deodorizer during a set of experiments, and always as a disinfectant at the end of the hour. Its own odor is easily washed away. As it takes some time for a porcelain cylinder to become thoroughly impregnated with an odorous solution, it is convenient to have test-tubes with tightly fitting corks, in which a number of cylinders may be put to soak at the same time. Unless they can be kept in a dark cupboard, it is well to wrap up these tubes in several plies of black calico. Bottles of yellow glass, such as perfumers recommend for the safe keeping of heliotropine, might well be used for all the solutions, but if they are not available, the ordinary bottles of colorless glass can be wrapped up in black cotton cloth. The less woolen cloth about the room, the better. We keep our solid cylinders in "self-sealing" preserve jars. When the cylinder with its fluid-mantle in place is not in use, the bore should be corked to keep the inner surface from drying off. It may, indeed, be filled with the solution and corked when it is put away for some time. In this case, all drops of liquid must be wiped out with absorbent cotton before the experiments begin. If it seems likely that much odorous substance has condensed on the inner surface, the whole bit of apparatus, glass shell and all, may be immersed in water. The bore should then be filled for a few hours with the odorous liquid.

The walls of the room in which our experiments were made are covered with oiled paper, and the floor is covered with oil-cloth which has a coating of shellac. The room has at present this defect, that when the wind blows in certain directions, it is impossible to create through it a draft of air which does not pass first through a hall frequented by students and therefore dusty, and by no means free from odor. When the standard olfactometer was used, the subject sat between the observer and the window, and at right angles to the observer, so that the light shone through the graduated inhaling-tube. When the fluid-mantle olfactometer was used, subject and observer sat at right angles to each other at the end of a low table.

CHAPTER III. RESULTS.

Section 1. The Several Subjects and their Stimulus-Limina.

Individual variations in the sense of smell are so great that it is necessary to preface a chapter on experimental results with an account of the subjects. The following notes upon our subjects in alphabetical order are thrown into "noun-form" for the sake of brevity.

Be. (Dr. I. M. Bentley), a *trained* subject.
Organ impaired by acute catarrhal troubles and easily exhausted.
Breathing spots always blurred and ragged at the division lines,—indicating a catarrhal condition of the membranes,—and never quite symmetrical.
$r\lambda$ usually determined with one *inspiration;* Δr determined with from 2 to 4 *inspirations.*
Movements of cylinder long and slow, but few.
Position indicative of strain.

Bi. (Miss E. M. Bickham), a wholly *untrained* subject. *General physical condition* neurasthenic.
Organ twice operated on (in '95 and '96) for hypertrophy of the

membranes. Superfluous portions removed from both sides. No catarrh now apparent.

Breathing spots usually well-rounded and symmetrical with neat division lines.

$r\lambda$ and Δr determined with but one *inspiration*.

Movements of cylinder rapid with little repetition.

Position indicative of strain.

C. (Miss M. H. Carter), a *partially trained* subject.

Organ very easily exhausted. Membranes subject to sudden congestions of blood and mucus upon nervous fatigue. Adenoid growth as a child. (The growth was not cut away, but disappeared of itself.)

Breathing spots ragged, ill-defined, and almost never symmetrical.

Breathing during an experiment irregular and violent. Tendency to sniff obstinate. $r\lambda$ and Δr usually determined with 1 or 2 *inspirations*.

Movements of cylinder rapid with little repetition.

Position indicative of much strain.

D. (Mr. S. J. Druskin), a *partially trained* subject.

Breathing spots perfect, as a rule.

$r\lambda$ and Δr usually determined with 1 or 2 *inspirations*.

Movements of cylinder at first rapid and few; after practice, tentative with noticeable repetition.

Position indicative of but slight strain.

K. (Mr. T. Kairiyama), a *trained* subject.

Organ much impaired by hay-fever and other catarrhal trouble.

Breathing spots fairly symmetrical as a rule, but ragged at the edges.

$r\lambda$ and Δr usually determined with 1 or 2 *inspirations*. Expiration violent ("to clean out the smell").

Movements of cylinder tentative but few.

Position indicative of but slight strain.

M. (Miss E. B. Macleod), a wholly *untrained* subject.

Breathing spots seldom quite symmetrical and never well defined. No catarrh before the current winter.

$r\lambda$ and Δr usually determined with 1 or 2 *inspirations*.

Movements of cylinder always irregular from want of practice.

Position easy.

N. (Mr. A. C. Nutt), a *partially trained* subject.

Organ: Easily exhausted. Sensitivity somewhat higher on the right side, as a rule. (The subject complained of "feeling left-handed" on the left side.)

Postero-lateral half of left *breathing-spot* usually missing (a fact showing chronic obstruction of the left inferior meatus). Both spots ill-defined.

$r\lambda$ and Δr determined usually with 2 or 3 *inspirations*.

Movements of cylinder slow and tentative with but little repetition.

Position indicative of strain.

P. (Mr. C. A. Perry), a *partially trained* subject.

Organ much impaired by chronic catarrh. Diseased portions removed from the lower turbinal bones on both sides.

Breathing spots rarely symmetrical. Secondary division quite apparent in spite of the operation mentioned. Spots ill-defined.

$r\lambda$ and Δr usually determined with one *inspiration*.

Movements of cylinder slow and tentative with but little repetition. *Position* indicative of but slight strain.

Rob. (Mr. E. P. Robins), a *trained* subject.
Breathing spots rarely symmetrical or perfectly defined.
$r\lambda$ and Δr almost invariably determined with one *inspiration.*
Movements of cylinder slow and tentative with but little repetition.
Position indicative of but little strain.

Rog. (Miss L. R. Rogers), a *partially trained* subject.
Breathing spots rarely symmetrical or very well defined.
$r\lambda$ and Δr usually determined with 2 or 3 *inspirations.*
Movements of cylinder slow with much repetition.
Position indicative of but slight strain.

Se. (Mr. W. B. Secor), a *trained* subject.
Organ: Sensitivity somewhat higher on the right side as a rule.
Postero-lateral half of left *breathing spot* usually very small or missing as with *N.* Spots ill-defined.
$r\lambda$ and Δr usually determined with 2 or 3 *inspirations, movements of cylinder* slow with some repetition.
Position indicative of strain.

Sh. (Dr. Stella E. Sharp), a *trained* subject.
General physieal condition neurasthenic.
Organ easily exhausted.
Right *breathing spot* usually larger than left, edges of both spots clearly cut.
$r\lambda$ and Δr usually determined with one *inspiration, movements of cylinder* slow with little repetition.
Position indicative of much strain.

T. (Dr. Ellen B. Talbot), a trained subject.
Organ somewhat easily exhausted. Portions of both lower turbinal bones removed to prevent congestions of mucous in the upper passages. Sensitivity somewhat higher on the left side.
Breathing spots well rounded and clearly cut. Secondary divisions imperfect. (When the nasal passages were clear the division was represented only by indentations at the edges of the spots.)
$r\lambda$ at first determined with one *inspiration*; later in the work, with 2, 3, or even 4 as a more satisfactory procedure. Δr usually determined with 2 or 3 inspirations.
Movements of cylinder very slow and cautious with much repetition.
Position indicative of but little strain.

In the notes just given a subject is called "trained" if he had had a fair amount of experience in general introspection. Only *Be.* had had any training in smell-experiments before the beginning of the course described in this paper. Some months earlier we had made a futile attempt to find his difference-limen with the weaker Utrecht cylinder of gutta-percha and gum ammoniac by the method of minimal changes. A subject is called "partially trained" if he began psychological laboratory-work about the time when these experiments commenced. The word "repetition" is used in connection with the manipulation of the cylinder to denote the moving backwards and forwards at the limen.

The breathing spots of all the subjects varied much from day to day. Sometimes they were broken up into several bands, always running rather from front to back than laterally. Often one narrow

medial strip would separate from one or the other. In most cases a more or less jagged and blurred outline showed the adhesion of clots of mucous to the passage-walls. In fact, twelve out of the thirteen subjects had suffered or were suffering from frequent "colds" or from hypersecretion more or less chronic. As a function of the turbinal bone is to deflect a part of the inspired air to the upper passages, its removal damages the sense of smell. The sensitivity of *T.* was higher on the left side of the nose, from which, as she reported, the smaller amount of bone had been taken, but the small remains of the secondary division of the breathing spots did not indicate that more bone had been removed on the one side than on the other. The obstruction of the inferior meatus would not, in itself, do much mischief to the sense, but it must indicate a dropping of mucous from the upper passages. It is of some interest to note that the subject (*D.*) whose spots are most perfect is a Russian. He came, however, to live in New York city at the age of twelve. *K.* is Japanese, but has been long enough in this country to suffer severely from the catarrhal climate. *Rob.*, one of the best subjects, comes from Prince Edward's Island. The homes of the other ten are scattered over the States from Eastern Massachusetts to California, though none are farther south than Missouri.[1]

When it is said that $\triangle r$ was determined with one, two, or more inspirations, it is meant that the stimulus of comparison was manipulated during one, two, or more inspirations. More than one inspiration was almost never taken to "learn" the standard. It seemed better to risk the increase of adhesion by allowing a subject to take as many breaths to a determination as he wished than to make him try to form a judgment when the force of an inhalation was decidedly on the wane. Many of the subjects considered a judgment with one inspiration an impracticable ideal. *D.*, *K.*, *Se.* and *Sh.*, and in a smaller measure *Be.* and *P.*, had a bad habit of suspending an inspiration, and not of sniffing, but of "holding the breath" momentarily during an inspiration. This practice must have tended to weaken the stimulus by allowing the air in the upper chamber to rush downwards to the middle meatus. *Be.*, *N.*, *P.*, *Rob.*, *Se.* and *T.* noticed that the stimulus was stronger during the latter part of an inspiration. This may point to cumulative stimulation of the rod-cells, or it may merely mean an access of attention and an unconscious sniff. *Se.*, who had the habit of suspending an inhalation, noticed the increase most after a strong inspiration, and *D.*, *K.* and *Sh.*, who had the same habit did not notice it at all. And it is clear that this peculiar mode of breathing would tend to prevent cumulative stimulation. On the other hand, *Be.*, *P.* and *T.* noticed the increase most when the stimulus was near its limen, and this looks as if it were a matter of attention and breathing-rate, especially as *T.* did not hold her breath. *Be.* remarked that the least difference of attention altered the stimulus. *Rob.* thought the first part of an inspiration gave the fairest measure of an intensity, and *Be.* and *Se.* relied on it "in easy judgments," but judged by the latter part of the inspiration if the stimulus were weak or vague. *N.* and *P.* asserted that they judged "by the impression as a whole," but *N.* confessed to a tendency "to emphasize the last whiff." *T.* reversed the procedure of *Be.* and *P.*, usually judging by "the last whiff," but repeating the inspiration and relying on the first impression if the determination were difficult. With *Rog.* exhaustion often supervened in a long inspiration. If is clear that if the intensity of

[1] Spraying the subject's nose at the beginning of the hour might be a useful expedient, but we did not try it.

a stimulus alters with the duration of an inspiration as well as with the manipulation of the instrument, the subject must make more than one inspiration to determine a limen, unless the judgment is very easy. It is probable that the first part of the inspiration, before the smell "blossoms out," gives the best criterion of the intensity of a stimulus. We would suggest that cumulative stimulation of smell would be a profitable subject of investigation.

In an effort to smell with the standard olfactometer, *C.*, *D.*, *K.*, *P.*, *Rob.*, *Rog.*, *Sh.* and *T.* all tipped the head to the left if using the left nostril, and to the right if using the right, pointed the outward end of the inhaling-tube in the same direction as the head was tipped, and slanted the screen in the opposite direction. This odd uniformity is perhaps explicable. On entering the nose the air ordinarily streams a little toward the septum and the opposite directions in which the subject slanted his head and the screen tended on each side to throw the opening of the nose-piece into an acute angle with the septum, while the turn given to the instrument in the horizontal plane threw the opening a little toward the front of the nose. On the other hand, *Se.* exactly reversed these directions on each side, and so did *Be.*, except that he turned the tube to point in the same direction as the screen was slanted, so throwing its inner opening towards the back of the nose. *Bi.* slanted both head and screen to the right when using the right nostril, and to the left when using the left. This was probably a mere matter of attention to one nostril or the other. She was not consistent in the pointing of the tube. *N.* turned everything to the right. Unfortunately, no written notes were taken of the hand used, but it was usually the right, the hand farther from the experimenter. All the subjects tended to tilt the hand forward and the screen backward,—probably in their desire to get "nearer" the stimulus. Almost all, unbidden, closed their eyes.

T. once mentioned verbal associations as an aid in memorizing the stimulus. This expedient was not common. *Be.* wrinkled his forehead and nose in a marked degree, and once noted a tendency to judge in terms of strain, especially about the eyes. Some substances were pungent to a disturbing extent to every one, but *C.* and *D.* complained much of "pain" from odors which no one else thought pungent. *D.* explicitly distinguished the sensation from pressure. He thought coumarine both pungent and "sour." Both *C.* and *D.* said that they received simply sensations of pressure from some stimuli. With *D.* sensations of smell merged in sensations of pressure as the organ became exhausted. *C.* said that when she tried to smell the black rubber with the left nostril she merely felt as if she were "breathing a feather," or as if the inside of her nose were "pressed with a soft wad." Yet the judgments made with this nostril agreed pretty well with those made with the other. *Be.* occasionally spoke of sensations of pressure or pain from the stimuli. Most of the subjects expressly denied temperature-associations. *Be.*, however, said that tolu and heliotropine were cold; *M.* that cocoa-butter was cold; *Rob.* that vanilline was cold; and *N.* that white tallow and musk-root were warm, and camphor cold, and that every smell grew warmer as it grew stronger. He thought of heliotrope as "warm, dark and deep," in contrast with ylang ylang, which was "light and fluffy."

The comparative sensitivity of the subjects may be judged from the following Table:

TABLE I. A TABLE OF STIMULUS-LIMINA.

Part I. Stimulus-Limina Arranged to Show Individual Variations.

SUBSTANCE.	Nostril.	Be	Bi.	C.	D.	K.	M.	N.	P.	Rob.	Rog.	Se.	Sh.	T.	Z.
		M	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.	Mm.
Black rubber,	R.	36		4	(22)	(43)	(35)	12		(61)	1	(12)	7	(38)	
	L.	34		5	(23)	(59)		11		(50)	1	(23)	10	(30)	
Gray rubber,	R.	9	(35)		1		(19)				(1)	5	(7)		
	L.	8	(29)		6		(22)				(1)	9	(10)		
Red rubber,	R.										(1)		(4)		7
	L.										(0)		(5)		
Russian leather,	R.	0				0								0	10
	L.	0				0								0	
Paraffine,	R.										12		(21)		10
	L.										20		(14)		
Rosewood,	R.					6		8	(54)			3			3
	L.					8		7	(67)			11			
Cedar,	R.			(4)				(27)		(10)			5	31	20
	L.			(5)				(29)		(12)			10	13	
Gum benzoin,	R.			7	7			(19)					(6)		10
	L.			8	7			(17)					(8)		
Gum ammoniac	(1) R.					(7)				(9)	(8)		(12)		
& gutta-percha:	(1) L.					(17)				(8)	(10)		(21)		
(1) First															
Utrecht cylinder,	(2) R.									(9)					
(2) Second															
Utrecht cylinder,	(2) L.									(8)					
(3) Home-made	(3) R.								9	2					
cylinder,	(3) L.								18	4					
Yellow wax,	R.														2.5
	L.														
Cocoa-butter,	R.	10	(16)				(7)		7						1
	L.	8	(17)				(4)		12						
Tolu balsam,	R.	14				4	1		(62)			1		9	1
	L.	19				3	1		(49)			6		5	
Musk-root,	R.							4				7			
	L.							8				5			
Mutton-tallow,	R.							4				2			
	L.							6				5			
Asafœtida,	R.	0				0								0	
	L.	0				0								0	
Oil of Mace.	R.			0	0	0		0	0	0		0			
	L.			0	0	0		0	0	0		0			
Coumarine,	R.	17	(2)	(20)	(6)	(8)	(1)		(25)	(12)	(12)	(4)	(27)	(36)	
	L.	23	(2)		(6)	(12)	(3)		(21)	(11)	(10)	(5)	(54)	(33)	
Glycerine soap,	R.						(19)		(12)	(7)					2
	L.						(15)		(13)	(4)					
Heliotropine,	R.	24						(33)						(9)	
	L.	39						(33)						(10)	
Musk.	R.					(8)						(7)			
	L.					(2)						(7)			

TABLE I.—*Continued.*

Part 2. Stimulus-Limina Arranged to Show Variations Due to Practice and to Differences of Temperature.

SUBJECT.	SUBSTANCE.	NOSTRIL.	Value of $r\lambda$ in cm.	THERMOMETER READING.
Be.	Tolu balsam	R.	(32)	53°F
		L.	(35)	
		R.	14	60
		L.	19	
K.		R.	(24)	54
		L.	(28)	
		R.	(21)	52
		L.	(22)	
		R.	4	64
		L.	3	
	Rosewood	R.	(16)	59
		L.	(29)	
		R.	(13)	64
		L.	(22)	
		R.	6	62
		L.	8	
P.	Cocoa butter	R.	(27)	62
		L.	(26)	
		R.	(19)	62
		L.	(27)	
		R.	7	66
		L.	12	

All the values of $r\lambda$ given in this Table are averages of several determinations taken on the same day. Those enclosed in parentheses were found when the subjects had had little or no experience with the substances in question. Those not so enclosed were found after the respective substances had been used by the several subjects in difference determinations. In the first part of the Table, the limen given is in every case the last limen found for the subject and substance, and all the last limina found are given. The second part of the Table simply contains results selected by way of illustration, but all the limina found for the subject with the substance in question are included.

In Part 1, all the substances but the last four are taken in order from a Table in which Zwaardemaker arranges various materials for solid odorous cylinders in the order of their intensity.[1] The limina in the column headed Z are those given by him in another Table as normal at a temperature of 15° C., or 59° F.[2] The temperatures at which our records were taken lay for the most part between 60° and 70° F. Our limina ought, therefore, to be lower than his, instead of higher. We cannot satisfactorily explain the difference between our results and his in the matter of stimulus-limina. That the limina of Americans should be higher than those of Dutchmen is not indeed surprising, but the entire change in the rank of the substances is. According to Dr. Reuter, as cited by Zwaardemaker, the gum ammoniac and gutta-percha cylinder is forty times as strong as the vulcan-

[1] *Op. cit.*, p. 118.
[2] P. 167.

ized rubber, and the musk-root is five times stronger than the former. The tallow, Zwaardemaker says, is stronger still. We regret that we could not find stimulus-limina oftener. The washing of the tube consumed so much time that this was impossible. We feel that the results embodied in Table I are the most unsatisfactory part of our work. Yet if allowances be made for exhaustion in some of the results of *C.* and *Sh.*, and for expectation gradually controlled by practice in the cases of *Bi.*, *M.* and *Rog.*, the Table will serve its purpose.[1]

We have not space to give our temperature records in full. They varied so irregularly that the arithmetical mean by no means represents the most common reading. As the steam had to be kept shut off when we were not in the laboratory, the exact regulation of the temperature involved serious practical difficulties, and for most of our work it was a matter of minor importance, for in difference-determinations variations of temperature and moisture affect the standard-stimulus and the stimulus of comparison equally, and may, therefore, be disregarded. Indeed, our barometer-records, though carefully kept, proved to be wholly a work of supererogation, for in the case of the very few substances (glycerine soap, coumarine, heliotropine, vanilline, and allyl sulphide) which were somewhat soluble in water and yet not in aqueous solution, we did not succeed in finding stimulus-limina on different days.[2] Practice lowered the stimulus-limina in a conspicuous manner, but the effect of variations in temperature can only occasionally be traced in the complete results. Part 2 of Table I illustrates this fact with fairness.

It only remains to say that *Be.*, *C.*, *K.*, *N.*, *Se.* and *T.* worked twice a week for at least part of the year and the others once.

Section 2. Results Obtained by the Method of Just Noticeable Differences.

Since in the nature of the case numerical proof of the applicability of Weber's law to a given sense department cannot be thrown into the form of averages, and since we have not space for the great mass of figures which we have at hand, we must offer first samples and then summaries of our evidence, and content ourselves with them. Tables II and III are the samples, and Tables IV, V and VI are summaries from different points of view. TableI V constitutes the most decisive proof of the validity of the law. Tables V and VI are intended to confirm the conclusion to be drawn from Table IV, and to show the probable value of $\frac{\Delta r}{r}$. In Tables III, IV, V and VI, *every value given or enumerated is an average* of the results of one day's work with one subject, nostril, substance and standard. All the work done with this method, however unsatisfactory, is represented in Tables V and VI.

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[1] The writer's own limina are lower than those of any of the subjects. Abnormal keenness of smell has persisted from childhood, in spite of the usual share of "colds."

[2] For the effect of atmospheric moisture in Zwaardemaker's method, see Chapter I, Section 2.

TABLE II. CONSECUTIVE RESULTS OF ONE SUBJECT, *T*.

DATE.	SUBSTANCE.	Nostril.	No. of values averaged.	r	Δro	Δru	Δr	$\frac{\Delta r}{r}$	Disturbing factors.
Nov. 9,	Tolu balsam	R.	6	20	4(2)	7(3)	5½	4	
		L.			5(2)	5(1)	5	4	
13,		R.	6	30	2(1)	14(2)	8	4	
		L.			3(2)	9(5)	6	5	
16,		R.	3,4	20	1(1)	6(4)	3½	6 [Z]	
		L.	3,3		4(2)	4(2)	4	5 [Z]	
		R.	4	30	6(3)	8(2)	7	4	
		L.			4(2)	7(4)	5½	5	
19,		R.	4,3	20	4(1)	1(2)	2½	Z [Z]	
		L.	3,3		5(3)	6(4)	5½	4 [Z]	
		R.	4	30	6(2)	7(3)	6½	5	
		L.			4(4)	5(3)	4½	Z	
30.	Russian leather,	R.	4,2	24	7(2)	3(1)	5	5 [Z]	
		L.			6(1)	5(2)	5½	4	
		R.	4	44	8(2)	9(2)	8½	5	
		L.			10(3)	12(3)	11	4	
Dec. 10,		R.	4	24	3(2)	6(2)	4½	5	
		L.			6(4)	7(2)	6½	4	
		R.	4	44	6(4)	10(3)	8	6	
		L.			8(3)	11(4)	9½	5	
14,	Asafœtida,	R.	3	8	5(4)	4(1)	4½	A	
		L.			6(0)	7(1)	6½	A	
		R.	3	13	4(3)	10(2)	7	A	
		L.	2,3		5(1)	8(1)	6½	2 [2]	
	Russian leather,	R.	2	9	5(3)	—	—	– [Z]	Exhaustion.
		L.	3,1		4(2)	0(–)	2	5 [6]	
16,	Asafœtida,	R.	2,1	8	3(3)	6(–)	4½	A [Z]	General fatigue. Exhaustion.
		L.	3,1		4(1)	3(–)	3½	2 [5]	
		R.	3	13	3(2)	6(2)	4½	3	
		L.	2,3		8(1)	5(2)	6½	2 [3]	
	Russian leather,	R.	3,2	9	6(4)	1(1)	3½	3 [3]	
		L.	3,1		5(1)	3(–)	4	2 [6]	
20.	Asafœtida,	R.	1,3	8	3(–)	3(2)	3	3 [Z]	Exhaustion.
		L.	1,1		3(–)	0(–)	1½	5 [–]	
		R.	3,2	13	6(1)	6(1)	6	2 [3]	
		L.	3,2		7(1)	3(2)	5	3 [3]	
	Russian leather,	R.	1,2	9	10(–)	1(2)	5½	A [6]	Exhaustion.
		L.	3,1		3(1)	1(–)	2	5 [Z]	
Jan. 8,	Cedar,	L.	4	22	8(2)	8(3)	8	3	Exhaustion.
11,		R.	4,2	22	8(2)	6(2)	7	3 [5]	Exhaustion. Pungency.
		L.	3,4		6(3)	8(3)	7	3 [4]	
		L.		42	11(1)	10(1)	10½	4	
22.	Asafœtida,	R.	2	12	8(4)	8(0)	8	A	General fatigue.
		L.			5(3)	8(1)	6½	A	
		R.	2	22	14(2)	13(2)	13½	A	
		L.			8(1)	14(0)	11	2	
Feb. 1,		R.	3	22	8(2)	8(1)	8	3	
		L.			8(3)	8(3)	8	3	
		R.	3	12	10(1)	8(1)	9	A	
		L.			9(2)	7(1)	8	A	
5,	Coumarine,	R.	3	56	14(2)	7(4)	10½	5	
12,	Heliotropine,	R.	4	28	15(2)	11(0)	13	2	

TABLE II.—*Continued.*

DATE.	SUBSTANCE.	Nostril.	No. of values averaged.	r	Δro	Δru	Δr	$\frac{\Delta r}{r}$	Disturbing factors.
Feb. 12,	Heliotropine,	L.			13(1)	11(2)	12	2	
		R.	3	48	18(0)	17(1)	17½	3	
		L.			20(2)	15(1)	17½	3	
18,		R.	2	28	17(0)	13(0)	15	A	
		L.			14(2)	11(0)	12½	2	
		R.	2	48	18(1)	15(0)	16½	3	
		L.			19(5)	14(0)	16½	3	
26.		R.	2	27	13(0)	10(0)	11½	2	
		L.			12(1)	8(1)	10	3	
		R.	2	47	19(1)	14(3)	16½	3	
		L.	1,2		16(–)	9(2)	12½	4	
Mar. 1,		R.	3	27	13(1)	8(0)	10½	3	General fatigue.
		L.			12(2)	8(0)	10	3	
		R.	3	47	18(1)	15(0)	16½	3	
		L.			18(0)	15(1)	16½	3	
3,	Valerianic acid,	R.	3	18	15(2)	9(1)	12	A	Pungency. Exhaustion.
		L.			14(2)	7(3)	10½	A	
		R.	2	38	18(1)	13(1)	15½	3	
		L.	2,3		16(2)	9(2)	12½	3	
8,		R.	2	18	13(1)	3(2)	8	2	
		L.	3		12(1)	4(2)	8	2	
		R.	2	38	16(2)	6(4)	11	4	
		L.	1,2		18(–)	5(0)	11½	3	
18,		R.	2,1	18	15(2)	4(–)	9½	A	General fatigue. Nose-bleed during the day.
		L.	2		15(3)	3(2)	9	2	
		R.	2,1	38	24(2)	11(–)	17½	2	
		L.	2		20(1)	11(0)	15½	3	
19,		R.	2,3	18	11(1)	5(1)	8	2	Irritation of nasal membranes. Exhaustion.
		L.	2		12(0)	—	—	—	
		R.	3,2	38	16(1)	10(4)	13	3	
		L.	2		17(1)	10(3)	13½	3	
21,		R.	3	18	13(1)	7(2)	10	A	Irritation of nasal membranes. Smell of tobacco.
		L.	3,2		13(0)	7(1)	10	A	
		R.	3	38	16(1)	13(1)	14½	3	
		L.	2		18(1)	11(2)	14½	3	
26.	Citral,	R.	2	13	8(1)	5(2)	6½	2	Irritation of nasal membranes. Homatropin freshly put into the eyes.
		L.	3,2		8(1)	4(2)	6	2	
		R.	2,1	28	13(0)	8(–)	10½	3	
		L.	3,2		12(2)	7(1)	9½	3	
Apr. 16,		R.	1,2	13	7(–)	0(0)	3½	4	
		L.	2		8(1)	2(1)	5	3	
		R.	3	28	12(0)	4(2)	8	4	
		L.	2,3		12(1)	5(2)	8½	3	

T. whose results seem best fitted to be used as an illustration, worked twice a week, as a rule, during the time covered by this Table. No difference-determinations obtained from her during this time by the method of just noticeable differences have been omitted. In October, we worked with her once a week, but were occupied chiefly in finding stimulus-limina. She also worked for us several hours late in the spring with results which did not differ materially from those embodied in the table. The fourth column of the Table gives the number of values averaged to obtain the figures given in the columns headed

Δro and Δru. If two figures stand on a line in the fourth column, the first refers to Δro and the second to Δru. One figurerefers not to both together but to each alike. The numbers in parentheses are all mean variations. A dash in parentheses means that the number by which it stands is not an average. In the column headed $\frac{\Delta r}{r}$, for the sake of brevity values greater than $\frac{1}{2}$ are indicated by the letter A; values equal to $\frac{1}{2}$ or less, but nearer to $\frac{1}{2}$ than to $\frac{1}{3}$, are indicated by the figure 2; values equal to $\frac{1}{3}$ or nearer to $\frac{1}{3}$ than to $\frac{1}{2}$ or to $\frac{1}{4}$, by the figure 3; values equal to $\frac{1}{4}$ or nearer to $\frac{1}{4}$ than to $\frac{1}{3}$ or to $\frac{1}{5}$, by the figure 4; values equal to $\frac{1}{5}$ or nearer to $\frac{1}{5}$ than to $\frac{1}{4}$ or to $\frac{1}{6}$, by the figure 5; values equal to $\frac{1}{6}$ or greater, but nearer to $\frac{1}{6}$ than to $\frac{1}{5}$, by the figure 6; and values less than $\frac{1}{6}$, by the letter Z. Every subject sometimes moved the cylinder beyond the standard, and the reading, if taken at all, could be written only as a minus quantity. This crossing of the standard almost never occurred with the fluid-mantle olfactometer, and when it did the error was so easily explained that the reading was not taken. Between November 9 and the time when the liquids were first used, two sets of averages were obtained, the first by excluding and the second by including these negative quantities when they occurred. In Tables IV, V and VI, only values representing no negative quantities and differing from averages of the same series with the addition of such quantities by less than $\frac{1}{4}$ are included in the enumeration. The averages enclosed in square brackets in Table II were found by including minus quantities in the average values of Δro and Δru. From all unbracketed averages, negative quantities are excluded. A dash in square brackets indicates that the corresponding value of Δr is itself a negative quantity.

The effect of some of the disturbing factors which are constant can best be illustrated in connection with this Table. Besides exhaustion, adhesion, and the tendency to judge in terms of hand-movement, which we call for short "the movement-error," some obstruction of the nasal passages, some slight compensating-smells, such as that of the absorbent cotton used to wipe the inhaling-tube, and some distraction of the attention in manipulating the large instrument, must be taken for granted with all the subjects. Only marked exhaustion is expressly noted in Table II. Another source of error which comes into operation with asafœtida, oil of mace, Russian leather, and all the liquids except coumarine, heliotropine and musk is the escape of odor between the cylinder and the tube. The effect of this circumstance, which was mentioned in Section 2 of Chapter 2, must be to make the value of $\frac{\Delta r}{r}$ too large, because it makes the standard larger than the instrument indicates. If, for example, r on the instrument is 20 mm., but really is 25 mm., and Δr is found to be 5 mm., then $\frac{\Delta r}{r}$ will be nominally $\frac{1}{4}$ while really it is $\frac{1}{5}$.

As we explained in discussing the disadvantages of the method of just noticeable differences, the effect of the movement-error is to make the value of $\frac{\Delta r}{r}$ smaller for the larger

standards, and thus to conceal the operation of Weber's law. If we look now at the values of $\frac{\Delta r}{r}$ in Table II, we shall see at a glance that this variation exists. It should be noted that no variation in the order of the standards will eliminate the movement-error. If the smaller standard is given first and a certain habit of movement acquired, this habit will make $\frac{\Delta r}{r}$ for the larger standard too small. If the habit is acquired in connection with the larger standard, it will make $\frac{\Delta r}{r}$ for the smaller too large. It is true that if the standards were alternated by single determinations, rather than by short series, a habit of movement would be less likely to establish itself, but such a procedure is excessively confusing to the subject in the case of smell, and, moreover, all work done with the smaller standard after the organ is blunted with the larger is more or less unsatisfactory. If the distance between the standards and the stimuli offered as decidedly greater or less were kept not absolutely but relatively equal, the movement-error would be concealed. The fact that these distances cannot be kept absolutely equal, if the stimulus of comparison is to be accepted as such by the subject, is in itself no small confirmation of Weber's law. As a matter of fact, they were kept as nearly equal as possible, both to avoid concealing the movement-error and to minimize exhaustion by strong stimuli. They often varied in the same series as the subject's organ became blunted to all differences and then recovered itself, but in general for a standard of 10 or 15 mm., the difference was made 10 mm.; for a standard of 20 or 30, 15; for a standard of 40 or 50, 20, and for a standard of 60 or 70, 25.

The moving back and forth at the limen is some safeguard against the error, yet the tendency of $\frac{\Delta r}{r}$ to be smaller for the larger standards is apparent in the results of subjects whose attention was good and whose movements were careful. Thus, it is particularly well-marked in the work of *Se.*, who was certainly not inferior to any of our subjects. Moreover, the same tendency showed itself when the different standards were used on different days, and a habit in such nice adjustments could scarcely persist from day to day or week to week with so little practice. If (1) the movement-error is one explanation of the variation, (2) the escape of odorous vapor is in some cases another. The equal though unmeasured increment is a larger fraction of the smaller standard than of the larger. If our standards are 20 and 40 and the increment is 4, while

$\frac{\triangle r}{r} = \frac{1}{4}$ in both cases, then $\triangle r$ will be 6 in one case and 11 in the other, and we must write the values of $\frac{\triangle r}{r}$ $\frac{24}{80}$ and $\frac{22}{80}$. We believe that (3) a fortuitous circumstance in connection with the standard olfactometer is another factor in the same result. Usually, the last movement made by the subject is an outward movement. He moves from a point decidedly different from the standard to subjective equality, and then a little way back again,—in and out once or oftener. In moving the cylinder the hand is apt to slip, and the accidental increment to $\triangle r$ is a larger fraction of the smaller standard than of the larger. Adhesion is not a factor in the case, for it is larger for the larger standard, varies with the length of the determination, has an opposite effect upon $\triangle ro$ and $\triangle ru$, and is balanced in an indefinite way by exhaustion.

It should be noted in Table II that at first $\triangle ru$ is usually slightly larger than $\triangle ro$, but that with practice this variation is reversed. The natural effect of exhaustion is to make $\triangle ro$ larger than $\triangle ru$, for exhaustion does not affect the standard stimulus and stimulus of comparison equally, but progresses all the time that the latter is manipulated. This tendency is in a manner checked by the time-error and by adhesion. (See Chapter I, Section 4.) Now *Be.*, the one subject who had had some experience in smell-experiments before the beginning of this course, tended from the first to make $\triangle ro$ greater than $\triangle ru$. All the other subjects at first made $\triangle ru$ greater than $\triangle ro$, but all except *Rog.*, *Se.* and *Sh.* changed the tendency with practice or began to do so. *Rob.*, *N.* and *T.* altered it very soon and decidedly. With *Se.* the values were usually almost equal. This alteration with practice seems to show that exhaustion causes more disturbance than adhesion and the time-error put together. This is what we should expect, for although the subject rested while the tube was being cleaned, yet the removal of adhesion was absolute, while the recuperation of the organ was less complete each time.[1] We never can be quite sure, however, whether exhaustion is really decreasing the strength of stimuli regularly, or is blunting all differences or making all movements haphazard. When a subject complained that his nose felt "hot," "dry," "rough," "scrapy," "sore," or "numb," his movements were often erratic, and the smaller stimulus sometimes seemed as strong as the larger, which probably stunned the already weary organ instantly. The dryness, no doubt, was due to the vigorous breathing. The tongue of a fever-patient will become much more parched and black if respiration through the nose is obstructed.

The original tendency to make $\triangle ro$ decidedly smaller than $\triangle ru$, and the difficulty of finding the lower stimulus-limen are probably due to the same cause. Both cumulative stimulation and memory after-images might produce the tendency, though both would be counteracted in a measure by the moving to and fro at the limen. Against both, the subject would learn to guard in a measure. *Be.* mentioned "after-images" of cocoa-butter, and *Se.* of tolu balsam. Frequently a subject would complain that he could not "get the strong smell out of his nose."

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[1] Zwaardemaker: *op. cit.*, pp. 203-204.

In the mean variations, as a whole, it is impossible to trace any tendency to be larger in judgments made with reference to the larger standard. Though the larger standard was usually given last, the effect of exhaustion in producing erratic judgments towards the end of the hour seems to have been balanced by a certain lack of practice. At the beginning of the hour, there is a sort of conscious awkwardness, characteristic of these smell-judgments when first attempted. It is impossible to draw from our figures any conclusion in regard to the delicacy of quantitative sensible discrimination in smell. The variations were evidently controlled to a great extent by the peculiarities of the instrument and the subject's habit of movement, and it must be confessed that from day to day the effect of practice upon them was not very clearly marked. All the subjects had smaller mean variations when using the fluid-mantle olfactometer, but this fact can hardly have been due to practice, for, although the other instrument was used first in every case, *Rob.*, *Rog.* and *T.* returned to it after using the large instrument for a while, and showed the same mean variations as they did at the beginning. Moreover, the difficulty of turning the screw-head of the large instrument and

TABLE III.

Complete Results for One Solid and One Liquid Substance.

SUBSTANCE.	SUBJECT.	VALUES OF $\frac{\Delta r}{r}$
Gray rubber,	Be.	$\frac{17}{36}$, $\frac{17}{36}$, $\frac{22}{74}$, $\frac{19}{74}$, $\frac{14}{36}$ w. $\frac{17}{74}$ and $\frac{35}{112}$, $\frac{7}{36}$ w. $\frac{21}{74}$ and $\frac{29}{112}$
	D.	$\frac{8}{38}$ w. $\frac{22}{78}$, $\frac{13}{38}$ w. $\frac{19}{78}$
	Se.	$\frac{14}{54}$ w. $\frac{18}{92}$, $\frac{15}{54}$ w. $\frac{19}{92}$, $\frac{15}{54}$ w. $\frac{13}{92}$, $\frac{14}{54}$ w. $\frac{20}{92}$
Coumarine,	Be.	$\frac{16}{52}$, $\frac{14}{52}$
	Bi.	$\frac{12}{32}$ w. $\frac{17}{72}$, $\frac{12}{32}$ w. $\frac{17}{72}$, $\frac{16}{32}$ w. $\frac{24}{72}$, $\frac{12}{32}$ w. $\frac{23}{72}$
	C.	$\frac{24}{92}$, $\frac{17}{52}$, $\frac{25}{92}$, $\frac{23}{52}$ w. $\frac{25}{92}$, $\frac{25}{52}$, $\frac{22}{52}$ w. $\frac{29}{92}$, $\frac{19}{52}$ w. $\frac{27}{92}$, $\frac{17}{52}$ w. $\frac{27}{92}$
	D.	$\frac{14}{32}$ w. $\frac{18}{72}$, $\frac{15}{32}$ w. $\frac{19}{72}$
	K.	$\frac{30}{72}$ w. $\frac{16}{112}$, $\frac{20}{72}$ w. $\frac{27}{112}$, $\frac{18}{72}$ w. $\frac{29}{112}$
	M.	$\frac{24}{52}$, $\frac{23}{52}$, $\frac{30}{52}$ w. $\frac{29}{92}$, $\frac{17}{52}$ w. $\frac{25}{92}$, $\frac{16}{52}$ w. $\frac{28}{92}$
	N.	$\frac{15}{112}$, $\frac{12}{112}$, $\frac{26}{72}$ w. $\frac{27}{112}$, $\frac{20}{72}$ w. $\frac{26}{112}$, $\frac{18}{72}$ w. $\frac{26}{112}$, $\frac{18}{72}$ w. $\frac{24}{112}$
	P.	$\frac{24}{72}$ w. $\frac{26}{112}$, $\frac{21}{72}$ w. $\frac{26}{112}$
	Rob.	$\frac{25}{72}$ w. $\frac{33}{132}$, $\frac{27}{72}$ w. $\frac{33}{132}$, $\frac{19}{72}$ w. $\frac{21}{32}$, $\frac{16}{72}$ w. $\frac{18}{32}$, $\frac{14}{32}$ w. $\frac{25}{72}$, $\frac{13}{32}$ w. $\frac{25}{72}$
	Rog.	$\frac{11}{52}$ w. $\frac{20}{92}$, $\frac{18}{52}$ w. $\frac{21}{92}$, $\frac{20}{52}$ w. $\frac{22}{92}$, $\frac{19}{52}$ w. $\frac{23}{92}$
	Se.	$\frac{17}{52}$ w. $\frac{23}{92}$, $\frac{17}{32}$ w. $\frac{28}{92}$, $\frac{21}{52}$ w. $\frac{26}{92}$, $\frac{26}{52}$ w. $\frac{26}{92}$
	Sh.	$\frac{18}{92}$, $\frac{27}{132}$, $\frac{11}{32}$ w. $\frac{23}{72}$, $\frac{11}{32}$ w. $\frac{20}{72}$
	T.	$\frac{21}{112}$

the propensity of the movable cylinder of the small instrument for slipping are quite enough to explain the fact. The mean variations of *Rob.*, *Rog.*, *Se.* and *Sh.* closely resembled those of *T.*, both in size and in degree of uniformity. Those of *Be.*, *Bi.*, *C.*, *M.* and *N.* ran higher, and were more irregular. This fact was undoubtedly due to hasty movements in the cases of *Bi.*, *C. and M.*, and to exhaustion in the cases of *Be.* and *N.* *D.*'s mean variations were large and irregular in the beginning, but improved with his manner of moving the cylinder, and *K.*'s also were large at first, but finally approximated to *T.*'s. *P.*'s were suspiciously small, as small with the fluid-mantle as with the standard olfactometer, and indicated the movement-error beyond a doubt.

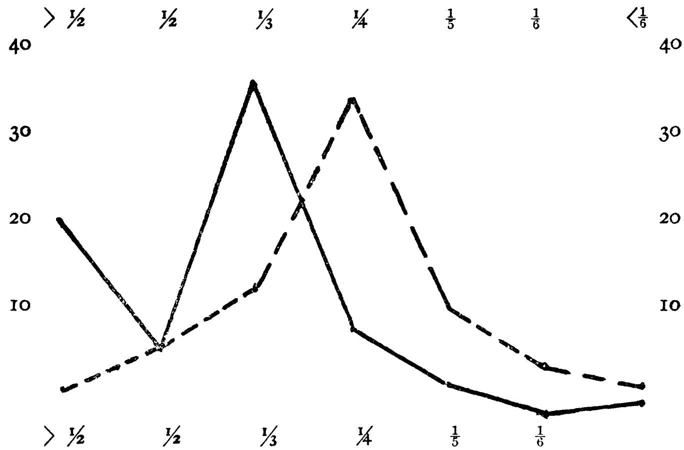
Results connected by W. ("with") were found on the same day for the same nostril. The values obtained with gray rubber were chosen for illustration because vulcanized rubber was used with three different methods, and those obtained with coumarine were taken because this scent was used with all the thirteen subjects. Both sets are fair samples of the whole mass of results. The series of *Be.* and *D.* with gray rubber, and of *Bi.*, *C.*, *K.*, *M.*, *N.*, *Rob.* and *Sh.* with coumarine, give pretty clear indications of the validity of Weber's law. That of *Se.* with rubber, and those of *D.*, *P.*, *Rog.* and *Sh.* with coumarine, indicate the operation of the law simply by the fact that as a rule the numerators of the fractions with the larger denominators are larger. The series of *Be.* and *T.* with coumarine are too short to prove anything by themselves. A series in which the numerators of the fractions with the larger denominators are persistently smaller than those of the fractions with the smaller denominators or equal to them may be counted as tending to disprove the law.

In the complete set of results—counting the results of one subject with one substance as one series—there are 55 series for solids. Out of these, 15 indicate Weber's law clearly; 14 indicate it faintly; 11 long

TABLE IV.

Approximate Values of $\frac{\Delta r}{r}$ *obtained for Pairs of Standard Stimulus-Intensities Sensed under the Same Conditions,—viz: Subject, Nostril, Substance, and Hour.*

$\frac{\Delta r}{r}$	(1) $r=a$	(2) $r=2a$ or $2a+$	(2) $r=a$	(2) $r=a+\langle a$	(1) $r=a$	(1) $r=2a$ or $2a+$	(2) $r=a$	(2) $r=a+\langle a$
A. V.	C.	C.	C.	C.	C.	C.	C.	C.
)½ (A)	20	3	14	11	10		7	1
½ (2)	7	7	5	5	35	1	14	4
⅓ (3)	34	13	7	10	35	57	46	32
¼ (4)	9	32	21	7	6	34	17	32
⅕ (5)	3	11	9	12	3	3	3	12
⅙ (6)		5	4	3	5		1	4
)⅙ (Z)	1	3	1	13	1		2	5
Total,	74	74	61	61	95	95	90	90



CURVES ILLUSTRATING THE VALUES OF $\frac{\Delta r}{r}$ FOR SOLIDS WHEN $r=a$ AND $2a$ OR $2a+$. (See Table IV.)

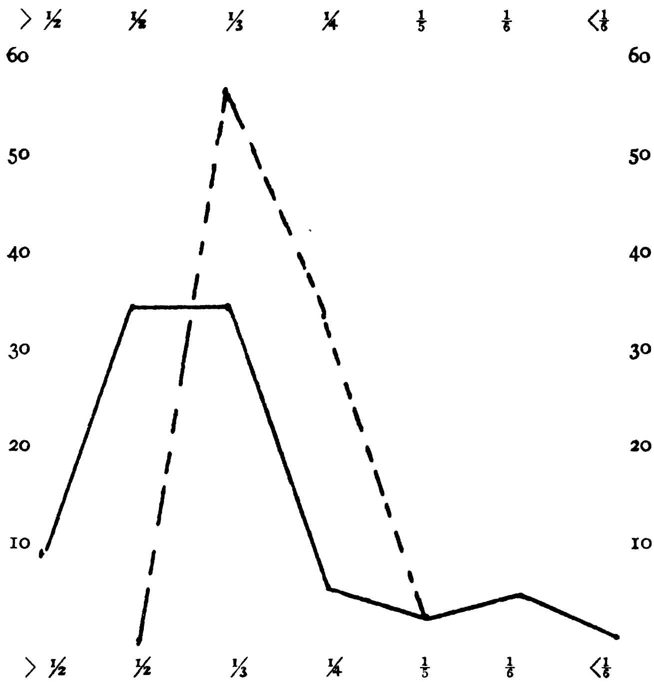
series are of doubtful interpretation; 13 series are too short to prove anything; and 2 tend to disprove the law. Out of 39 series for liquids, 24 indicate the law clearly, and 11 do so faintly, while 3 are too short to count, and only 1 tends to disprove the law.

We may now proceed to the Tables which summarize the evidence.

As noted before, Table IV enumerates only values for standards which can be paired as sensed under the same conditions. The left column of each pair of columns enumerates values obtained for the smaller standards in the pairs. The columns headed (1) enumerate values for standards of which one was twice as strong as the other, or more than twice as strong. The columns headed (2) enumerate values for standards of which one was less than twice as strong as the other. All values obtained for standards which can be paired are included. *A. V.* stands for "Approximate Values," and *C.* for "Cases."

We believe that we have accounted for the tendency of $\frac{\Delta r}{r}$ to be somewhat smaller for the larger standards. In Table IV, however, it is clear that the errors to which this tendency is due do not serve to conceal the operation of Weber's law. If certain absolute differences of smell-intensity were sensed and $\frac{\Delta r}{r}$ for a given standard were ⅓, then for a standard twice as strong it should be ⅙, not ¼.

Tables V and VI are arranged to show such variations as occur from subject to subject, and substance to substance. That it may be seen that each subject used a variety of substances, and that the different subjects used the substances in different



CURVES ILLUSTRATING THE VALUES OF $\frac{\Delta r}{r}$ FOR LIQUIDS WHEN $r=a$ AND $2a$ OR $2a+$. (See Table IV.)

Of these curves, the heavy lines give the values for the smaller, and the broken lines for the larger standards. The ordinates give the number of cases, and the abscissæ approximate values.

orders, we preface the Tables with the following list of substances as used in order by each subject:

Be. Black rubber, tolu, cocoa-butter, asafœtida, Russian leather, gray rubber, coumarine, heliotropine, valerianic acid, citral.

Bi. Cocoa-butter, coumarine, vanilline.

C. Gum benzoin, oil of mace, cedar, coumarine.

D. Gray rubber, gum benzoin, oil of mace, coumarine, oil of camphor.

K. Tolu, rose-wood, asafœtida, Russian leather, gum ammoniac and gutta-percha from Utrecht, oil of mace, coumarine, musk, ethyl butyrate.

M. Cocoa-butter, coumarine.

N. Black rubber, tallow, musk-root, rose-wood, oil of mace, heliotropine, oil of camphor, vanilline.

P. Gum ammoniac and gutta-percha, home-made, glycerine soap, oil of mace, coumarine, oil of camphor.

Rob. Glycerine soap, gum ammoniac and gutta-percha, home-made, oil of mace, coumarine, vanilline, cedar, gum ammoniac and gutta-percha from Utrecht.

Rog. Black rubber, paraffine, coumarine, oil of camphor, caryophylline, gum benzoin, oil of anise, laudanum.

Se. Tolu, rose-wood, tallow, asafœtida, musk-root, gray rubber, oil of mace, coumarine, musk, ethyl butyrate, citral, caryophylline, allyl suphide.

Sh. Black rubber, cedar, gum ammoniac and gutta-percha, from Utrecht, coumarine, oil of camphor.

T. Tolu, Russian leather, asafœtida, cedar, coumarine, heliotropine, valerianic acid, citral, pyridin and yellow wax.

The fact that the order was not varied more extensively and more systematically was due to practical difficulties with the apparatus.

TABLE V. APPROXIMATE VALUES OF $\frac{\Delta r}{r}$ ARRANGED TO SHOW VARIATIONS FOR INDIVIDUAL SUBJECTS.

Subject.	Nature of Stimuli	Number of Cases (approximating or equal to)							Total number of cases.
		$\geqq \frac{1}{2}$ (A)	$\frac{1}{2}$ (2)	$\frac{1}{3}$ (3)	$\frac{1}{4}$ (4)	$\frac{1}{5}$ (5)	$\frac{1}{6}$ (6)	$< \frac{1}{6}$ (Z)	
Be.	S.	6	9	4	6	3	1		29
	L.	5	5	16	5	5	1	1	38
Bi.	S.				4	4	1	3	12
	L.		1	9	4	1	3	2	20
C.	S.	6	2	7	3	5	1	2	26
	L.		3	6	3				12
D.	S.	9	4	3	6	1			23
	L.		7	6	3				16
K.	S.	3	6	13	5	1			28
	L.	2	6	12	9			1	30
M.	S.						1	2	3
	L.	1	2	4	1				8
N.	S.	4	2	13	13	5	3	8	48
	L.	1	1	10	7	3		2	24
P.	S.			5	4	2	1	2	14
	L.			3	6	4		3	16
Rob.	S.	16	4	10	11	1	2		44
	L.	2	1	8	7	1	1		20
Rog.	S.		1	4	5	5	3		18
	L.		1	21	6	3		1	32
Se.	S.	8	4	11	14	10	3	2	52
	L.	1	19	40	29	3			92
Sh.	S.			2	2	4		4	12
	L.		1	9	3	4		1	18
T.	S.	8	5	11	13	10	2	2	51
	L.	6	11	24	6	1	4		52
Total,		78	95	251	175	76	27	36	738

It will be seen that there is very little variation in the value of $\frac{\triangle r}{r}$ from class to class of substances. All of Zwaardemaker's classes are represented among either the solids or the liquids except Class IX, that of nauseating smells. We could not obtain *Anagyris fœtida* or Indian stink-wood ("Scatolholz") in the American market, and we did not try soon enough to get it from Europe. Variations in the results of individual subjects are, however, due to variations in the substances used.

TABLE VI.

Approximate Values of $\frac{\triangle r}{r}$ arranged to show Variations for Different Substances.

PART I. SOLIDS.

SUBSTANCE.	Number of cases {equal to or approximating}							Total number of cases.
	>$\frac{1}{2}$(A)	$\frac{1}{2}$(2)	$\frac{1}{3}$(3)	$\frac{1}{4}$(4)	$\frac{1}{5}$(5)	$\frac{1}{6}$(6)	<$\frac{1}{6}$(Z)	
Yellow wax. I,	—	1	3	4				8
Russian leather. I,	2	4	3	5	6	1		21
Oil of mace. II,	25	11	10	4				50
Cocoa-butter. II (?),		3	2	5	5	3	5	23
Rosewood. II,	1		10	10	2	1		24
Cedar. II,			9	2	3		4	18
Tolu balsam. III,			2	8	6	2	2	20
Gum benzoin. III,	6	2	8	6	5	2	1	30
Musk-root. IV,		1	6	7	2	1	3	20
Black rubber. V,		1	4	5	6	4	6	26
Gray rubber. V,		2	4	10	5		1	22
Asafœtida. V,	14	6	5					25
Gum ammoniac and gutta-percha.								
(1) Weaker cylinder fr. Utrecht,	1	3	4	3	2		1	14
(2) Stronger cylinder fr. Utrecht,	1	1	5	7	1	1		16
(3) Home-made cylinder,	10	2	1		1		1	15
Paraffine. VII,				3	3	2		8
Mutton-tallow. VII,			5	3	4			12
Glycerine soap,			2	4		1	1	8
Total,	60	37	83	86	51	18	25	360
Values for oil of mace, asafœtida, and home-made cylinder of gum ammoniac and gutta-percha,	49	19	16	4	1		1	90
Final result,	11	18	67	82	50	18	24	270

TABLE VI.—*Continued.*

Approximate Values of $\frac{\Delta r}{r}$ *arranged to show Variations for Different Substances.*

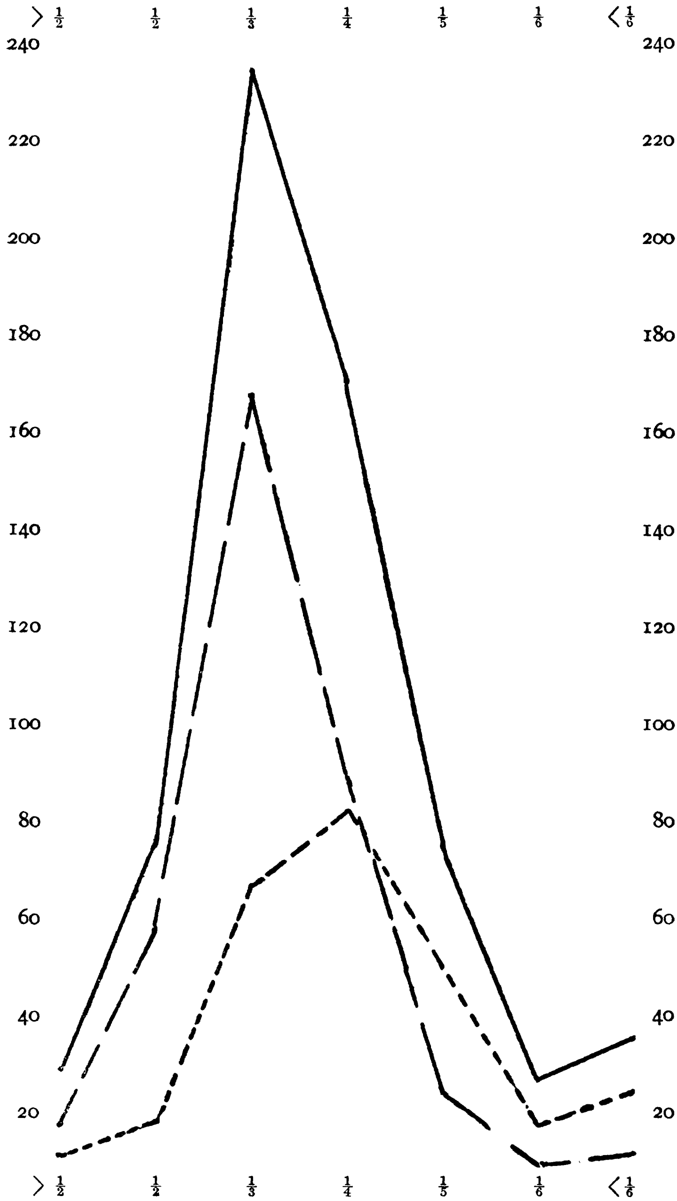
PART II. LIQUIDS.

SUBSTANCE.	Number of cases { equal to or approximating }							Total number of cases.
	>½(A)	½(2)	⅓(3)	¼(4)	⅕(5)	⅙(6)	<⅙(Z)	
Oil of camphor. II,	1	7	26	8	6		4	52
Caryophylline. II,	1	2	10	5	2			20
Oil of anise. II,			6	1	1			8
Valerianic acid. II,	10	7	12	2				31
Ethyl butyrate. II,	2	12	8	6				28
Citral. II,		8	26	9	1			44
Vanilline. III,			10	7	1	4	2	24
Coumarine. III,	3	11	34	31	7		3	89
Heliotropine. III,	1	4	14	3	6	1	1	30
Musk. IV,		2	15	6	1			24
Allyl sulphide. V,		5	3	8				16
Pyridin. VI,			2	2		4		8
Laudanum. VIII,			2	1			1	4
Total,	18	58	168	89	25	9	11	378

PART III. SOLIDS AND LIQUIDS.

Nature of Stimulus.	Number of cases { equal to or approximating }							Total number of cases.
	>½(A)	½(2)	⅓(3)	¼(4)	⅕(5)	⅙(6)	<⅙(Z)	
Solid,	11	18	67	82	50	18	24	270
Liquid,	18	58	168	89	25	9	11	378
Total,	29	76	235	171	75	27	35	648

Almost all the values for solids in which $\frac{\Delta r}{r}$ exceeds ½ were obtained with asafœtida, oil of mace, or the home-made cylinder of gutta-percha and gum ammoniac. Thus, out of 9 values in which *D.* exceeded ½ for solids, 7 were found with oil of mace, and out of 16 values in which *Rob.* exceeded ½, 10 were found with the home-made cylinder of gutta-percha and gum ammoniac, and 4 with oil of mace. We believe that it is perfectly fair to exclude these cylinders from our final results. And if we do so there is little variation from substance to substance. The odor of asafœtida and oil of mace was very perceptible when the instrument was closed, and the mace would



CURVES SHOWING THE APPROXIMATE VALUES OF $\frac{\Delta r}{r}$ IN THE WHOLE COURSE OF EXPERIMENTS BY THE METHOD OF JUST NOTICEABLE DIFFERENCES. (See Table VI, Part 3.)

The heavy line gives the values for both solids and liquids; the dotted line gives the values for solids, and the broken line for liquids. The ordinates give the number of cases, and the abscissæ approximate values.

scrape off on the inhaling-tube. While Zwaardemaker's mixture of gum ammoniac and gutta-percha is black and brittle like licorice, ours was yellowish gray, contained strings of gutta-percha, and made the inhaling-tube cloudy and sticky. We did succeed in obtaining stimulus-limina with it when the inhaling-tube was first cleaned, but we believe that the end of the tube was probably soiled most of the time during difference-determinations. We have not excluded the results for Russian leather because its odor, like that of most of the liquids, was just liminal when the instrument was closed, and the results harmonized with the others. Since most of the liquids had this error of the equal but unmeasured increment, it is not surprising that the values of $\frac{\Delta r}{r}$ run higher for them than for solids. It will be noticed that they run highest for valerianic acid, which was particularly troublesome in escaping from the instrument. Yet as the results for coumarine, heliotropine, and musk show 1/3 as the most common value, we must conclude *that the value of* $\frac{\Delta r}{r}$ lies *somewhere between* 1/3 *and* 1/4.

Some of the substances showed an interesting difference of quality with difference of intensity. Thus several subjects thought that oil of camphor smelt like nutmeg when weak, and like turpentine when strong. The slight odor of the paraffine appeared when a strong stimulus was given with coumarine. *T.* said that heliotropine smelled like heliotrope on the left (the better) side of her nose, and like bitter-almonds on the right. (As a matter of fact the two smells are closely allied.) *Se.* said that the tallow smelled like onions in his poorer nostril. Fluctuations at the limen were also noted. Coumarine and heliotropine, when weak, were said to come "in whiffs" or "waves," and *K.* always spoke of weak smells as "scattered."

Section 3. Results of Other Methods.

Table VII gives some of the results obtained by the method of just noticeable differences modified in the direction of the method of minimal changes, as described in Chapter I, Section 4, and shows the agreement of these results with those reached by the ordinary method. *C. M.* stands for "Combination Method."

We used red rubber with the true method of minimal changes because Zwaardemaker had done so. The cylinder was obtained from Utrecht. The experiments of which the results are given in Table VIII extended through five laboratory-hours. It is needless to say that the instrument was manipulated entirely by the experimenter.

TABLE VII.

Results of the Modified Form of the Method of Just Noticeable Differences.

SUBJECT.	SUB-STANCE.	METHOD AND Standard	NOSTRIL	No. Values Averaged.	$\Delta ro'$	$\Delta ro''$	$\Delta ru''$	$\Delta ru'$	Δro	Δru	Δr	$\frac{\Delta r}{r}$
D.	Gray rubber,	C. M. $r=19$	R.	4	9	8	6	10	9	8	8½	2
			L.		11	8	3	7	10	5	7½	3
		C. M. $r=39$	R.	4	18	9	3	11	14	7	10½	4
			L.		18	9	4	8	14	6	10	4
		J N D $r=19$	R.	4					2	6	4	5
			L.						7	6	6½	3
		J N D $r=39$	R.	4					12	10	11	4
			L.						9	10	9½	4
K.	Rose-wood,	C. M. $r=22$	R.	3	15	5	2	11	10	7	8½	3
			L.		11	6	3	16	9	10	9½	2
		C. M. $r=42$	R.	4	14	4	5	8	9	7	8	5
			L.		12	6	9	14	9	12	10½	4
		C. M. $r=22$	R.	2	10	5	7	10	8	9	8½	3
			L.		8	7	8	4	8	6	7	3
		C. M. $r=42$	R.	2	10	6	3	9	8	6	7	6
			L.		11	6	4	10	9	7	8	5
		J N D $r=22$	R.						9	9	9	3
			L.						13	15	14	A
		J N D $r=42$	R.						8	16	12	4
			L.						7	14	10½	4

TABLE VIII.

Results obtained for Red Rubber by the True Method of Minimal Changes.

SUBJECT—SH.

$r=20$ mm. Gradation $=2$ mm.

$\overset{\wedge}{\Delta r}=40$ mm. $\overset{\vee}{\Delta r}=4$ mm.

	r_1 given before r.			r given before r_1.		
	$\Delta ro'$	$\Delta ro''$	Δro	$\Delta ro'$	$\Delta ro''$	Δro
R. N.	6	6	6	12	6	9
L. N.	6	10	8	6	8	7
	$\Delta ru'$	$\Delta ru''$	Δru	$\Delta ru'$	$\Delta ru''$	Δru
R. N.	12	6	9	6	12	9
L. N.	8	4	6	8	12	10

	Δr	$\frac{\Delta r}{r}$	Δr	$\frac{\Delta r}{r}$
R. N.	$7\frac{1}{2}$	$\frac{15}{40}=\frac{1}{3}+$	9	$\frac{18}{40}=\frac{1}{2}-$
L. N.	7	$\frac{14}{40}=\frac{1}{3}+$	$8\frac{1}{2}$	$\frac{17}{40}=\frac{1}{3}+$

Final result: R. N. $\Delta r=8\frac{1}{4}$ mm. $\frac{\Delta r}{r}=\frac{33}{80}=\frac{1}{3}+$

L. N. $\Delta r=7\frac{3}{4}$ mm. $\frac{\Delta r}{r}=\frac{31}{80}=\frac{1}{3}+$

Zwaardemaker concluded that for a standard of from 2 to 5 cm., the difference limen was about 1.5 cm., and that for a standard of from 5 to 9 cm., it was about 3.5 cm. This would make the value of $\frac{\Delta r}{r}$ run from about ⅓ to about ¾. Our own results agree fairly well with his, and are a very pretty confirmation of the results obtained by the method of just noticeable differences. The writer intends to use the method of minimal changes much farther.

In contrast with these excellent results are those of the next Table:

TABLE IX.

Results obtained by the Method of Right and Wrong Cases.

SUBJECTS—C., D., K., N., ROB., ROG., AND T.

Instrument—Standard Olfactometer. Substances—*Black Rubber or Tolu Balsam.*

r and r_1.	Right Cases.	Wrong Cases.	Mistakes made in taking the Second Stimulus for Weaker when Stronger.	Total Number of Cases.
20 and 25	37	19	12	56
50 and 70	30	10	9	40
20 and 30	47	19	12	66
30 and 50	33	11	5	44
20 and 40	42	22	18	64
30 and 60	4	2		6
20 and 50	39	11	8	50
20 and 60	7	1	1	8

The stimuli given were never equal, and the judgment "equal" was counted a mistake. The results of all the subjects are massed.

As we said before, while exhaustion makes the errors nearly all run in one direction, confusion due to the unfamiliarity of olfactometric work is probably most at fault. More experiments should be made with the standard olfactometer and trained subjects. It is difficult to use the large olfactometer with this method, because the intervals between stimuli must be made very long or the subject can guess from the time spent in manipulation how they have been changed.

As a rough method of testing the applicability of the method of right and wrong cases to smell, we blind-folded one subject, stopped his ears with absorbent cotton, and required him to tell which way we had moved from a given standard on the large olfactometer. The results are given in the following Table:

TABLE X.

Results of a Rough Attempt to Gauge the Applicability of the Method of Right and Wrong Cases to Smell.

SUBJECT—K. SUBSTANCE—ETHYL BUTYRATE

Change.	Correct judgments of direction.	Incorrect judgments of direction.	Failures to note change or to distinguish its direction.	Total number of cases.	Change.	Correct judgments of direction.	Incorrect judgments of direction.	Failures to note change or to distinguish its direction.	Total number of cases.
Mm.					Mm.				
20 to 30	95	46	11	152	40 to 60	100	35	6	141
20 to 10	115	27	6	148	60 to 40	106	29	5	140

We see that here again the number of mistakes was very large. Yet these were the last experiments made with *K.*, who had worked for us twice a week throughout the year, and who had used butyric ether successfully in experiments by the method of just noticeable differences. He was, however, very tired at the time these last experiments were made. The second stimulus still is more often mistakenly taken for the weaker than for the stronger, showing that in these experiments also exhaustion outweighed adhesion and the time-error put together. (The tube was cleaned after every eight comparisons.)

SUMMARY AND CONCLUSION.

In beginning our investigations, we saw that we could not isolate simple olfactory qualities, and that an attempt to prove Weber's law for smell was justified only by the assumption that it might apply to fusions. We also saw that the fact that some olfactory qualities show but few grades of intensity pointed to a rise towards the terminal intensity by geometrical progression. Although Zwaardemaker explains the fact partly by the supposition that different smells have different difference-limina, we believe that two smells with the same difference-limen may exhaust the human sense-organ with very unequal degrees of rapidity, so that one may reach the terminal intensity much sooner than the other.

Aside from the condition of the sense-organ, the intensity of a smell depends (1) on the amount of odorous surface exposed to the air, (2) on the time that it is exposed, (3) on the condition of the air in regard to temperature, moisture, etc., which controls the rate of evaporation, (4) on the diffusion-rate of the

vapor, and (5) on the rate and manner of the subject's breathing. The great incidental difficulties in olfactometric work are (1) the variability of the organ through obstruction by mucus or (2) exhaustion, (3) the adhesion of the odorous matter to parts of the apparatus, and (4) the presence of compensating smells. The freedom of the nasal passages may be tested, but exhaustion can neither be prevented nor measured, nor can adhesion and the presence of compensating odors be absolutely excluded. We employed Zwaardemaker's olfactometric method in which (1) the measure is the amount of odorous surface exposed, (2) the time of exposure may be disregarded, (3) the diffusion-rate of vapor is under control, and (4) the subject's breathing is supposed to be self-regulating. We did not (5) succeed in regulating the temperature of our laboratory, but its variability was not of primary importance in difference-determinations. Adhesion makes the method of minimal changes impracticable for most substances with Zwaardemaker's method of smell-measurement, and exhaustion contributes to make the method of right and wrong cases very difficult. We therefore used the method of just noticeable differences. This psychophysical method involves an error from the subject's tendency to judge in terms of hand-movement. Another occasional source of error, incidental to our apparatus, was the escape of some odors between the inhaling-tube and cylinder. Both of these circumstances tend to make the values of $\frac{\triangle r}{r}$ smaller for the larger standards. Adhesion and the ordinary time-error tend to balance exhaustion. In spite of the four most serious sources of error, (1) exhaustion, (2) adhesion, (3) the movement-error, and (4) the unmeasured increment to some stimuli, we found $\frac{\triangle r}{r}$ to be about $\frac{1}{3}$ in 36% and about $\frac{1}{4}$ in 26% of our determinations. It was about $\frac{1}{2}$ in 12%, about $\frac{1}{5}$ in 12%, about $\frac{1}{6}$ in 4%, greater than $\frac{1}{2}$ in 5% and less than $\frac{1}{6}$ in 5% of the determinations. The slight use we made of the other gradation-methods confirms the general result. There is no great variation from one substance to another, or from one of Zwaardemaker's classes to another.

There is much yet to be done and said in olfactometric work —"of making of books there might be no end"—but we believe that enough has been said and done to offer some evidence that Weber's law applies to smell and that the value of $\frac{\triangle r}{r}$ lies between one-third and one-fourth.